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The Groundwater Atlas of Lancaster County

Dana Divine
University of Nebraska-Lincoln, ddivine2@unl.edu

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Cartography by Leslie M. Howard
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Conservation and Survey Division
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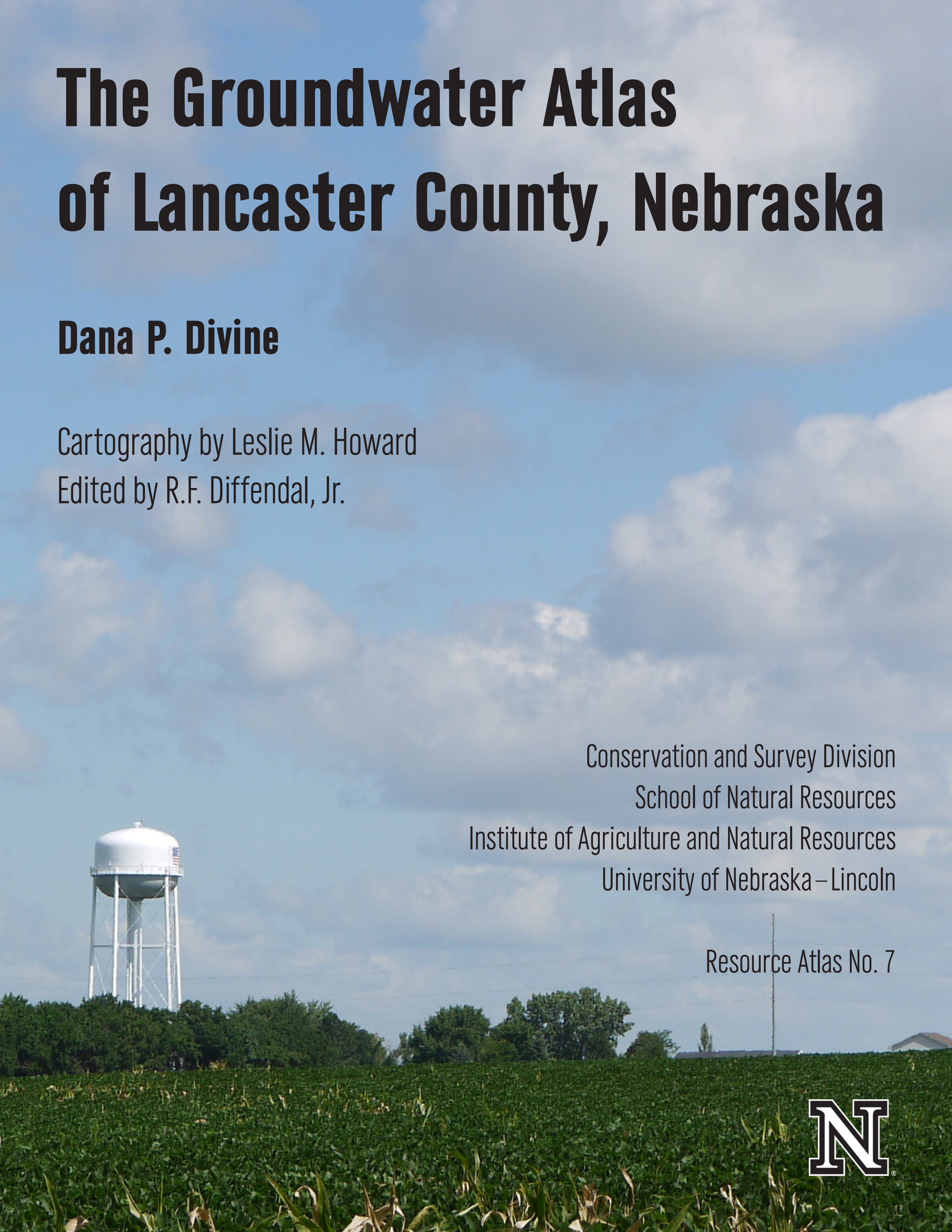

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The Conservation and Survey Division of the University of Nebraska–Lincoln is the agency designated by statute to investigate and interpret the geologically related natural resources of the state, to make available to the public the results of these investigations, and to assist in the development and conservation of these resources. It consists of program areas in geology, water, and soils.

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ABSTRACT

The purpose of this groundwater atlas is to synthesize a wealth of hydrogeologic data that exists for Lancaster County that has not been published in readily accessible formats. Many of the maps presented herein are based on registered well logs and test hole logs that are publically available on-line, which become more valuable when compiled, analyzed, and discussed.

In Lancaster County, the primary aquifers are relatively young unconsolidated sediments of the Quaternary System (2.58 million years old or younger). The thickest accumulations of saturated Quaternary material occur in two paleovalleys eroded into bedrock. Bedrock consists of the Dakota Group (100-145 million years old) and Permian and Pennsylvanian rocks (252-323 million years old). The Dakota Group is the uppermost bedrock unit in approximately three-fourths of the county, the exceptions being the southeastern part and in the northeast, where Permian and Pennsylvanian rocks are the uppermost bedrock. The largest paleovalley is the Dorchester-Sterling paleovalley in the southern part of the county where the saturated thickness of sand and gravel ranges from approximately 70 to 220 feet and transmissivity values can be greater than 50,000 gallons per day per foot (gpd/ft). The other paleovalley is northeast of Lincoln underlying the Salt Creek valley. The saturated thickness in this paleovalley ranges from approximately 10 to 100 feet with maximum transmissivity values greater than 20,000 gpd/ft. In addition to the primary Quaternary aquifers, the Dakota Group serves as a secondary aquifer in places. The transmissivity of the Dakota aquifer appears to be greatest in and around Lincoln, however the transmissivity values calculated for the Dakota aquifer in this atlas should be considered minimums because many of the bore holes and wells probably do not penetrate the entire thickness of the aquifer.

Salt Creek is the primary drainage in Lancaster County. In the northern part of the county, groundwater in the Quaternary aquifers generally flows toward Salt Creek or its tributaries. In southern Lancaster County, Quaternary groundwater flow directions are variable due to several groundwater highs and a complex hydrogeologic framework within the Dorchester-Sterling paleovalley. Groundwater flow directions in the Dakota aquifer in the northern part of the county generally mimic those in the Quaternary aquifers. Water levels in the Dakota aquifer underlying the Dorchester-Sterling paleovalley and in the Permian/Pennsylvanian bedrock are not well defined, although the groundwater flow patterns in the Permian/ Pennsylvanian bedrock are apparently different from patterns in the overlying Quaternary aquifers.

Confluence of Antelope Creek, Salt Creek, and Oak Creek.

Quaternary aquifers in Lancaster County probably receive an average of about 2.3 inches of recharge annually. The locations and mechanisms of this recharge are not well understood and are the subject of continuing investigation. Water quality in the Quaternary aquifers is generally good, with nitrate being the contaminant of most concern. Elevated nitrate concentrations are currently being managed in the vicinity of Salt Creek northeast of Lincoln and near the communities of Davey and Hickman. The water quality in the Dakota aquifer can be good, or it may have naturally high concentrations of salt or other dissolved ions. The distribution of salty or mineralized water in the Dakota aquifer is not well known, although chloride concentrations are generally highest in Lincoln and beyond the northern and western city limits. Saline water in the Dakota aquifer probably came from the underlying Paleozoic rocks and moved into the Dakota aquifer from either natural or induced upward gradients.

Lincoln Water System storage tank in south Lincoln, Nebraska

INTRODUCTION

Purpose and Scope

Government agencies, private businesses, and landowners recognize county-scale hydrogeologic summaries as valuable resources. The Conservation and Survey Division of the University of Nebraska (CSD) and the U.S. Geological Survey have published county-wide hydrogeologic reports for 29 of the 93 counties in Nebraska, most of which were produced in the 1960s and 1970s. Despite a relative abundance of groundwater information for Lancaster County, no county-wide report has been published previously.

The primary purpose of this atlas is to assist professionals in making water-related decisions or enhancing their own study of Lancaster County. The Geographic Information System (GIS) files used to make the figures are available on compact disc. Readers who are interested in broadening their general understanding of groundwater concepts or groundwater as a statewide resource can refer to the Groundwater Atlas of Nebraska (Korus et al., 2013a) for more information.

Methods and Limitations

Geologic logs from registered wells were the primary sources of data used to develop most of the maps in this atlas. The CSD test hole database and some unpublished test hole logs archived at CSD were also used, but they were few in number relative to registered well logs. Many geologic and hydrogeologic studies have been done in the county. Information from those reports provides much of the background necessary to understand the hydrogeology of the county. Those studies are cited throughout this atlas.

The water level, transmissivity, and bedrock contour maps in this atlas were made using ESRI's geostatistical analysis ordinary kriging interpolation method (ESRI ArcMap 10.0). Interpolation is a way of estimating values where no data exist. Almost all of the data used in this atlas was collected from discrete points (bore holes). Any information at a point without a bore hole must be estimated, and therefore, most of the data presented in the maps are estimates. Kriging is a geostatistical method that assigns weights to values at existing data points based on a pattern of spatial continuity (determined by a semivariogram) and then estimates a best fit surface. The surface estimated by kriging does not necessarily pass through the data points, and since the method seeks to best fit intermediate values, the high and low points in the data set will likely be smoothed out. Users of the GIS files (available on compact disc) will need to keep in mind that the maps were made based on geostatistical calculations of best fit, because in many cases the values at discrete data points do not match the generalized value depicted by a contour line. The variety of information used to make the maps combined with the inherent variability of geologic data creates a fair amount of uncertainty on the maps, yet recognizable patterns emerge and provide useful hydrogeologic information that was previously unavailable.

The location of the data points and the standard error on the interpolation are included as subset maps. Standard error is the standard deviation divided by the square root of the number of samples. In this atlas, the standard error is generally higher (the predicted value is less certain) in areas having few data points. Standard error has the same units as the original data. The standard error calculated for these maps is the error introduced by the interpolation only. The information depicted on the maps probably also deviates from actual conditions due to inaccuracies in well locations, imprecise land surface elevations, the subjective nature of recording and interpreting geologic material, and other factors. These uncertainties can be classified as measurement error and are the reason the kriged surfaces do not pass through the data points (Paciorek, 2008).

The subjective nature of recording and interpreting geologic material has a direct bearing on the accuracy and precision of the figures presented in this atlas. The bedrock map probably contains significant measurement errors because of differences in the way people logged the same sediment and rock types. Bedrock is sometimes specifically identified on well logs, but in areas where the uppermost bedrock is soft mudstone of the Dakota Group, positive identification of the material as bedrock is not easy and the material may have been logged as clay. Recognizing the difference between soft mudstone of the Dakota Group and soft shale of the Permian/Pennsylvanian is also not always obvious in the field, which introduces some ambiguity to the data. Another source of geologic uncertainty common in Lancaster County well logs is the description of localized calcium carbonate nodules within the Quaternary as "limestone". Limestone does consist primarily of calcium carbonate, but unlike the nodules found in Quaternary deposits, limestone bedrock is laterally continuous over large areas and is important hydrogeologically because fresh groundwater is not found in significant quantities within or beneath limestone bedrock in Lancaster County.

GEOLOGIC MAPS

Geographic Setting

The topography of Lancaster County is almost entirely rolling hills dissected by stream valleys (Korus et al., 2013a) (Fig. 1). Material at the land surface consists mostly of loess, till, and alluvium. Soils maps have been published for the county that show these materials and the soils which form on them (USDA, 2014). Surficial geology has been mapped in eight of the twelve 7.5-minute topographic quadrangles in Lancaster County to date. Detailed material descriptions and maps of surficial geology are published as part of the U.S. Geological Survey STATEMAP program (e.g. Hanson et al., 2012; Joeckel, 2007; Joeckel and Dillon, 2007; Joeckel and Howard, 2009; Young et al., 2010).

The rolling hills consist of loess-mantled glacial till. Loess is wind-blown silt. The silt probably originated west of Lancaster County in the Sand Hills region of central Nebraska and accumulated on the grass-covered surfaces of weathered glacial till hills (Reed and Dreeszen, 1965). Glacial till is a poorly-sorted mixture of silt, clay, sand, gravel, and boulders deposited by melting glaciers during repeated cycles of glacial advance and retreat that occurred in eastern Nebraska between 2.58 million and 600,000 years ago (Reed et al., 1966). This period is colloquially known as part of the Ice Age, which occurred during the geologic time period known as the Quaternary (Fig. 2). The prehistoric presence of glacial ice sheets in eastern Nebraska shaped much of the hydrogeologic framework of the unconsolidated Quaternary material above bedrock and makes it markedly different from the hydrogeologic framework of western Nebraska, where the High Plains Regional Aquifer System is present beyond the western edge of the glacial advance.

Salt Creek is the main surface drainage in Lancaster County. Of the 46 drainages in the county, all but seven drain into Salt Creek. These seven are located in the southeastern corner of the county and feed into the Nemaha River drainage system. Major tributaries of Salt Creek are Olive Creek, Oak Creek, Stevens Creek, and Little Salt Creek. U.S. Geological Survey stream gauges on Salt Creek at Roca and near the eastern county line indicate that the stream flow at these locations has averaged approximately 35 cubic feet per second (cfs) and 340 cfs, respectively, over the past decade. The nearly tenfold increase is caused in part by the addition of water from the City of Lincoln wastewater treatment plants, located between the two gauges.

The extent of hydrologic connection between the streams and groundwater in Lancaster County is not well understood. The degree of physical connectivity between surface water and groundwater depends on a variety of factors including the sediment type in the streambed (i.e. sand, silt, etc.), and the sediment types that occur under the streambed and above an aquifer. The degree of actual hydrologic connection between groundwater and surface water is a function of the aquifer materials plus additional factors such as the elevation of the water table and the elevation of surface water in the stream. If the streambed and underlying sediments are relatively permeable and the elevation of the water table in the vicinity of the stream is higher than the elevation of the water surface in the stream, then groundwater will flow into the stream, in which case the stream is said to be gaining. Conversely, if the water level in the stream is higher than the water table in the vicinity

Exposure of loess west of Lincoln, Nebraska.

of the stream, water will leave the stream to recharge the groundwater and the stream is referred to as losing (Winter et al., 1999). Given that elevations of surface water and groundwater both change over time, it is not uncommon for reaches of streams to switch between gaining and losing (Wang, 2012).

In-depth study is typically necessary to determine the degree of hydrologic connection between surface water and groundwater and if a stream is gaining or losing. A

Conservation and Survey Division drilling and logging a test hole northeast of Lincoln, Nebraska in 2012
Photo credit: Sharon Skipton, UNL Extension

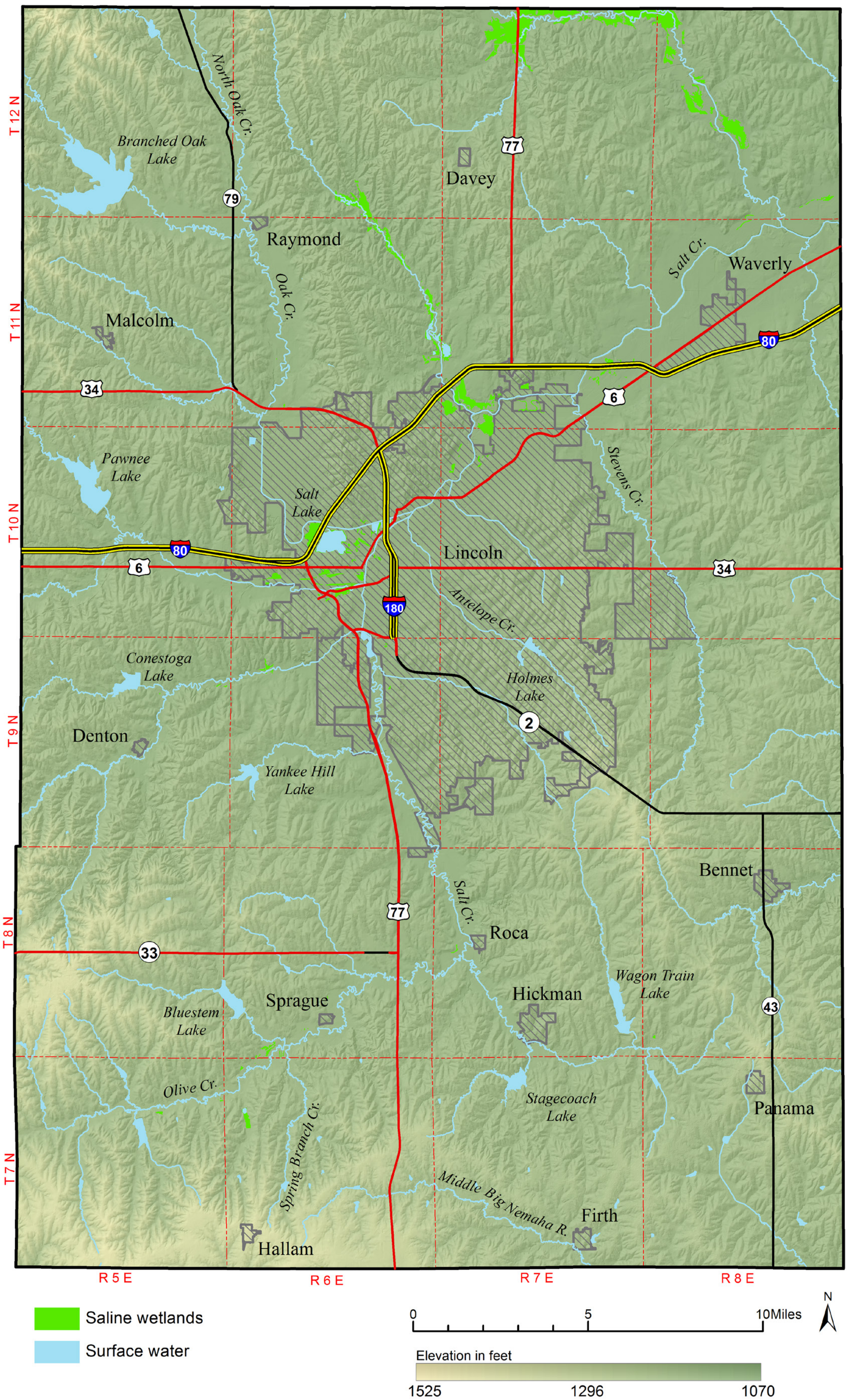


Figure 1. Geographic Setting. Rolling hills consist primarily of glacial till and loess dissected by numerous creeks. Salt Creek is the primary drainage in the county.

Era	Period	Epoch	Group	Formation	Thickness (ft)	Lithology	Age (Ma)†
Cenozoic	Quaternary	Holocene			0 to 400+	Alluvium (silt, sand, gravel)	0.0117
		Pleistocene				Loess and glacial till (clay, silt, sand, gravel)	2.58
	Neogene				Absent		
	Paleogene						66.0
Mesozoic	Cretaceous	Late	Colorado	Greenhorn	20 to 30	Chalky limestone	
				Graneros	20 to 30	Gray shale	100.5
		Early	Dakota	Woodbury	0 to 400+	Sandstone and shale	
				Nishnabotna		Sandstone and shale	145.0
	Jurassic				Absent		201.3
	Triassic				Absent		252.2
Paleozoic	Permian	Big Blue	Chase		Absent		
			Council Grove		0 to 300+	Limestone and shale	
			Admire			Shale and thin limestone	299.0
	Pennsylvanian	Virgil	Wabaunsee		< 100 to 550	Shale, limestone, sandstone, coal	
			Shawnee			Limestone and shale	
			Douglas			Shale and limestone	
		Missouri	Lansing		200 to 250+	Limestone and shale	
			Kansas City			Limestone and shale	
		Des Moines	Marmaton		< 100 to 200+	Shale, limestone, coal	
			Cherokee			Shale, sandstone, coal	323.0
	Mississippian				Absent		359.0
	Devonian				0 to 175	Dolomite and limestone	419.0
	Silurian				50 to 350	Cherty dolomite	443.0
	Ordovician				525 to 650	Dolomite, shale, and sandstone	485.0
	Cambrian				0 to 225	Dolomite and sandstone	541.0
Precambrian						Igneous and sedimentary rocks	

The shaded rock units are exposed at or near land surface.

† Million years ago

Chart modified from R. R. Burchett (unpublished) using information from Burchett et al. (1972), Wigley et al. (2004), and Cohen et al. (2014).

Figure 2. Geologic Time Scale. Youngest deposits are shown at the top of the table, oldest at the bottom. The complete stratigraphic section is shown to provide context, although Permian and Pennsylvanian rocks are the oldest mentioned in this atlas.

few streams in Lancaster County have been studied in this regard. Salt Creek east of Lincoln is probably connected to groundwater in a few locations (Korus, 2011). Southwest of Lincoln, Olive Creek and Salt Creek appear to have very limited connection with groundwater, although Spring Branch appears to be connected to a shallow aquifer for about 2.5 miles of its approximately six mile length, and is probably a losing stream where connected (Divine and Korus, 2012).

Bedrock Geology

Consolidated bedrock lies below the unconsolidated Quaternary deposits (Fig. 3). The bedrock in Lancaster County is of two ages. The youngest bedrock unit is the Cretaceous Dakota Group, which was deposited approximately 100-145 million years ago at the migrating margin of the Cretaceous Western Interior Seaway. The near-shore, beach, and fluvial depositional environments there resulted in deposition of variable lithologies including sandstone, siltstone, mudstone, shale, sand, and gravel. Erosion of the Dakota Group occurred during the 98 million years that separate the deposition of the Dakota from the deposition of the overlying Quaternary deposits, producing an unconformable Quaternary-Cretaceous contact. The Dakota aquifer consists of saturated sandstone and unconsolidated sand and gravel and is an important secondary aquifer in Lancaster County. The water in the aquifer may be brackish or saline and highly mineralized. Several detailed maps of the Dakota Group in Lancaster County were used in the preparation of this atlas. These maps include: contours of the top and bottom of the Group; total thickness; thickness of sandstone, sand, and gravel; and point values for total dissolved solids (Wigley et al., 2004). The Dakota aquifer referred to in this atlas is formally named the Maha aquifer, which is the upper aquifer in the Great Plains aquifer system (U.S. Geological Survey, 1997; Korus and Joeckel, 2011). The formal name was assigned for clarity across states, but since this atlas focuses on one county within Nebraska, the informal "Dakota aquifer" nomenclature will be used.

Outcrop of Dakota sandstone west of Lincoln, Nebraska.

Permian and Pennsylvanian limestone, shale, mudstone, and evaporites, deposited approximately 252-323 million years ago when shallow seas covered Nebraska, directly underlie Quaternary and Cretaceous deposits in Lancaster County. The Geologic Bedrock Map of Nebraska (Burchett, 1986) distinguishes between Permian and Pennsylvanian rocks, but this distinction is not very important hydrogeologically and the rocks of these ages will be grouped in this atlas as Permian/Pennsylvanian. Permian/Pennsylvanian bedrock is not typically considered an aquifer in Lancaster County, but there are a few low-yield wells in the vicinity of Hickman, where limestone beds of these ages are fractured enough to transmit water. Cretaceous and Permian/Pennsylvanian bedrock sometimes crops out along valley sides and in other places in Lancaster County. Older bedrock units occur under the units discussed above (Fig. 2), but they do not crop out and are not sources of fresh water in Lancaster County.

Paleovalleys are the most important feature of the bedrock surface in Lancaster County with regard to groundwater. Paleovalleys formed when eastward-draining streams incised valleys into bedrock during an erosional period after bedrock deposition and before glaciation (Ginsburg, 1983). Two such paleovalleys occur in Lancaster County (Figs. 3-5). The deeper and wider of the two, the Dorchester-Sterling paleovalley, extends through southern Lancaster County. This paleovalley is filled with thick sequences of sand and gravel, the ages of which are not well constrained (Korus et al, 2013b). The second paleovalley enters Lancaster County near Malcom, extends under north Lincoln, and then turns northeast and exits the east side of the county northeast of Waverly. Northeast of Lincoln the Salt Creek valley coincides with the paleovalley, and hence this aquifer

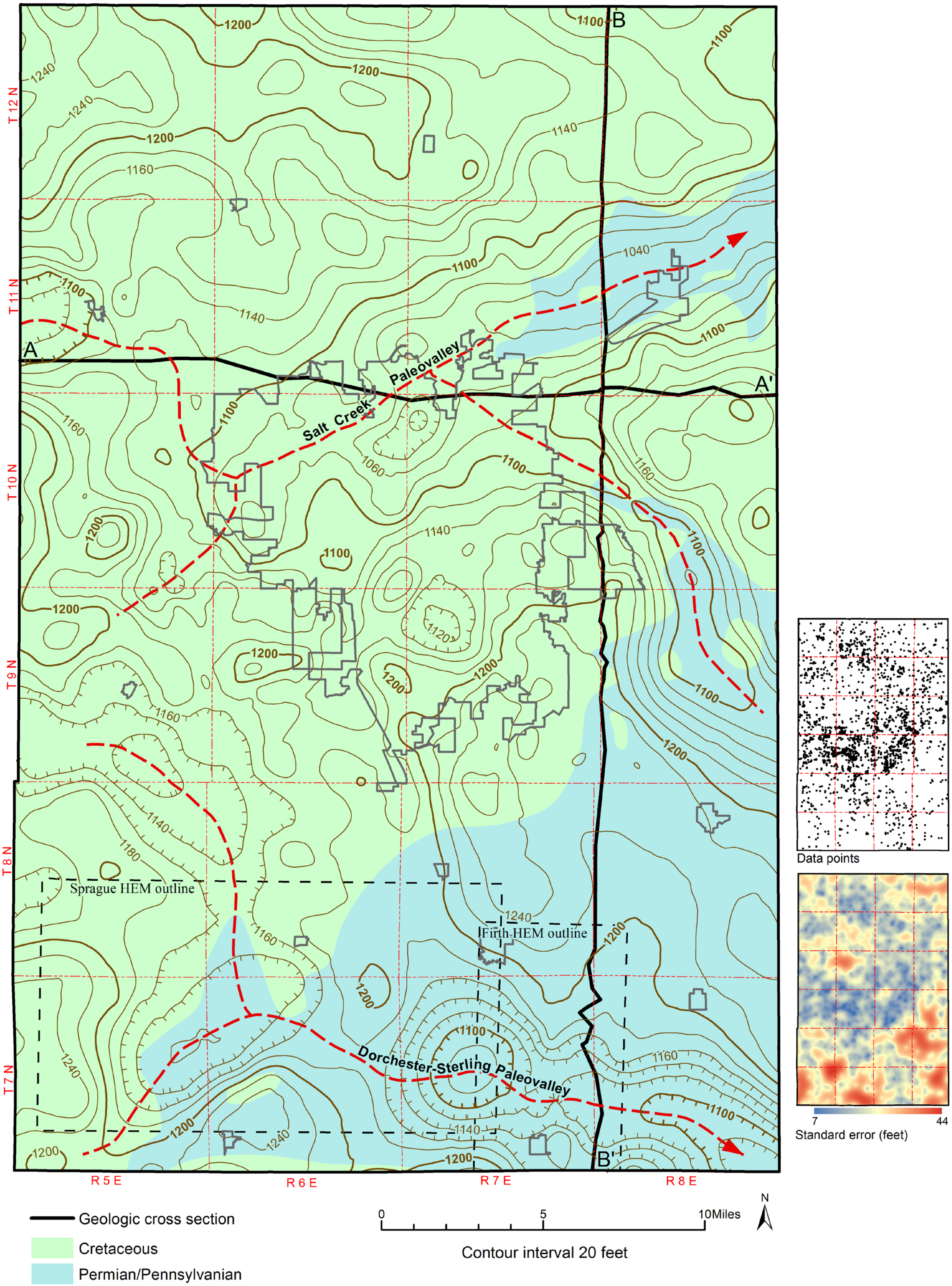
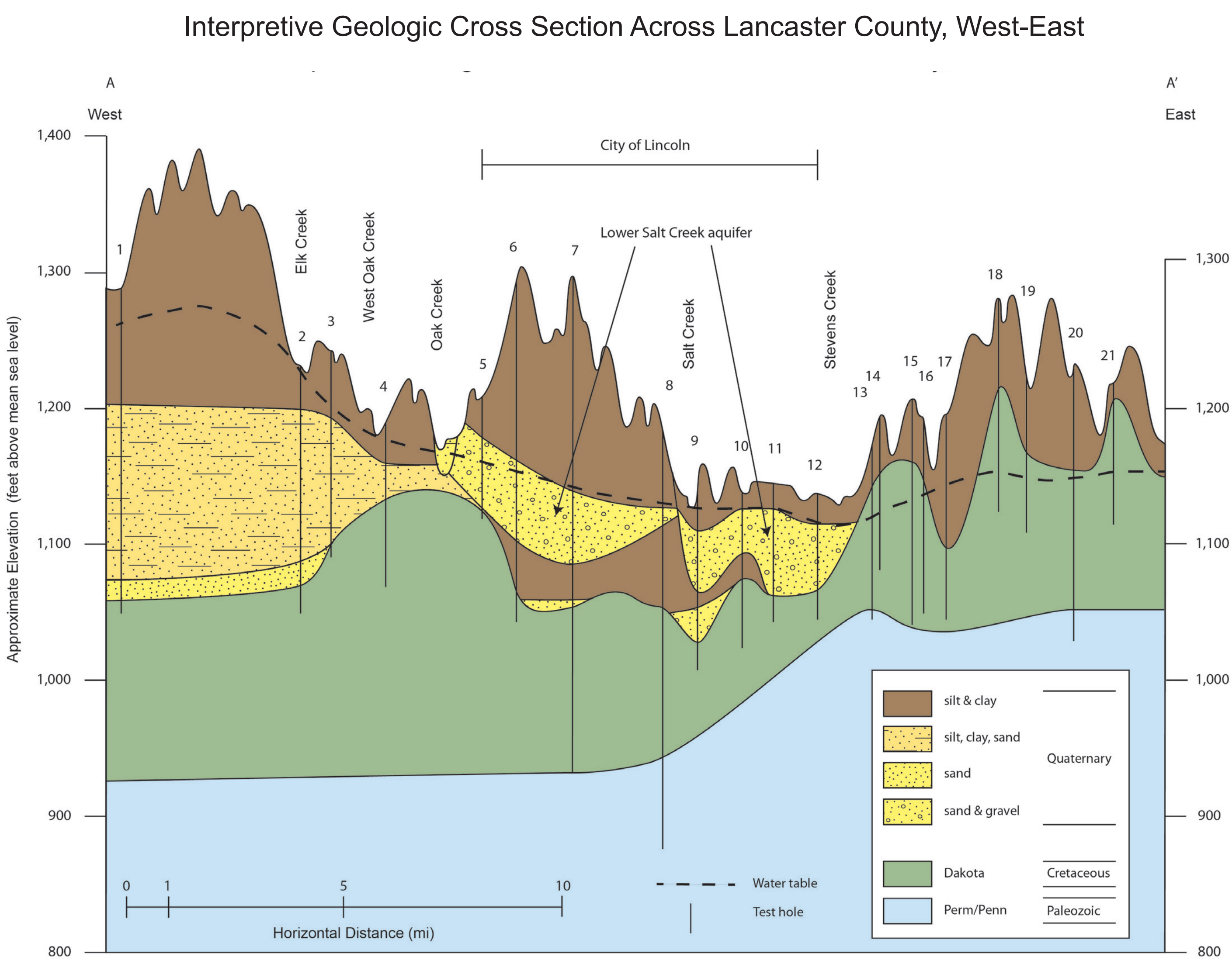


Figure 3. Elevation of Top of Bedrock. The bedrock surface consists of Cretaceous Dakota Group (green) and Permian/Pennsylvanian units (blue). Red dashed lines delineate paleovalley axes.

is called the Lower Salt Creek aquifer (LPSNRD, 2014a). Coincident modern valleys and paleovalleys are not the norm; more often no surface expression of the paleovalley exists (Ginsburg, 1983).

The paleovalley underlying Salt Creek northeast of Lincoln has the most well-defined valley, including an apparent tributary entering from the southeast (Fig. 3). The Dakota Group has been completely eroded in parts of the paleovalley and the southeastern tributary. In these areas Permian/Pennsylvanian bedrock directly underlies unconsolidated Quaternary material. The saturated thickness of the Quaternary material in this paleovalley ranges from approximately 10 to 100 feet thick. A detailed groundwater flow model of the Lower Salt Creek aquifer provides additional hydrogeologic information in this area (Korus, 2011). The segment of this paleovalley west of Lincoln is also shown on figure 3, although this part of the valley is not as deep and the Dakota has not been completely eroded.

The Dorchester-Sterling paleovalley in southern Lancaster County contains much greater thicknesses of saturated sand and gravel than the northern paleovalley even though the valley walls are not as steep. The saturated thickness of the Dorchester-Sterling paleovalley fill ranges from



Modified from: J. Headrick and D. C. Gosselin, 1996, Generalized Geologic Cross-Sections for Groundwater Regions (Region 11--Southeastern Glacial Drift Area)(CCS 17.11)

Figure 4. Interpretive Geologic Cross Section A-A', West-East. The location of this cross section is shown on figure 3. The dashed horizontal line is an estimated water level elevation and the solid vertical lines represent the locations (Appendix A) of bore holes or registered well logs. Loess, till, silt, and clay deposits are not subdivided.

approximately 70 to 220 feet thick. Uncertainty regarding the bedrock configuration of the paleovalley is greatest on the west side because unconsolidated Quaternary sand directly overlies Dakota sand and sandstone and the bedrock contact is difficult to identify. In the eastern part of the valley, the Dakota is completely eroded and the contact between Quaternary sand and Permian/Pennsylvanian limestone and shale is easier to discern. Even with these uncertainties, there is clearly relief on the bedrock surface and the elevation of the base of the paleovalley is irregular (Fig. 3).

At some locations, especially in the paleovalleys, few test holes penetrate to bedrock and lithologic logs consisting entirely of Quaternary deposits were used as an upper limit on the bedrock surface (Fig. 3). Inclusion of these data provides some control on the bedrock surface where none was available previously, but the bedrock surface depicted in these areas may be higher than in reality.

Interpretive Geologic Cross Sections

The locations of geologic cross sections were selected to illustrate the hydrogeologic variability of Lancaster County. The west-east section (Fig. 4) cuts across the northern paleovalley. The western part of the paleovalley (west of Oak Creek, Figs. 1 and 4) is filled mostly with silt that does not yield large amounts of water. Some sand and gravel is present in the paleovalley between Oak Creek and Stevens Creek (Figs. 1 and 4), creating a paleovalley aquifer called the Lower Salt Creek aquifer. The paleovalley extends through Lancaster County, but trends off the cross section to the northeast. The remainder of the cross section east of Lincoln shows the irregular Dakota surface overlain by unconsolidated Quaternary material.

The north-south geologic cross section (Fig. 5) starts at Rock Creek, where saline wetlands occur and the hydrostatic head is at or above ground surface (Sorenson, 2005). The section crosses the Salt Creek paleovalley northeast of

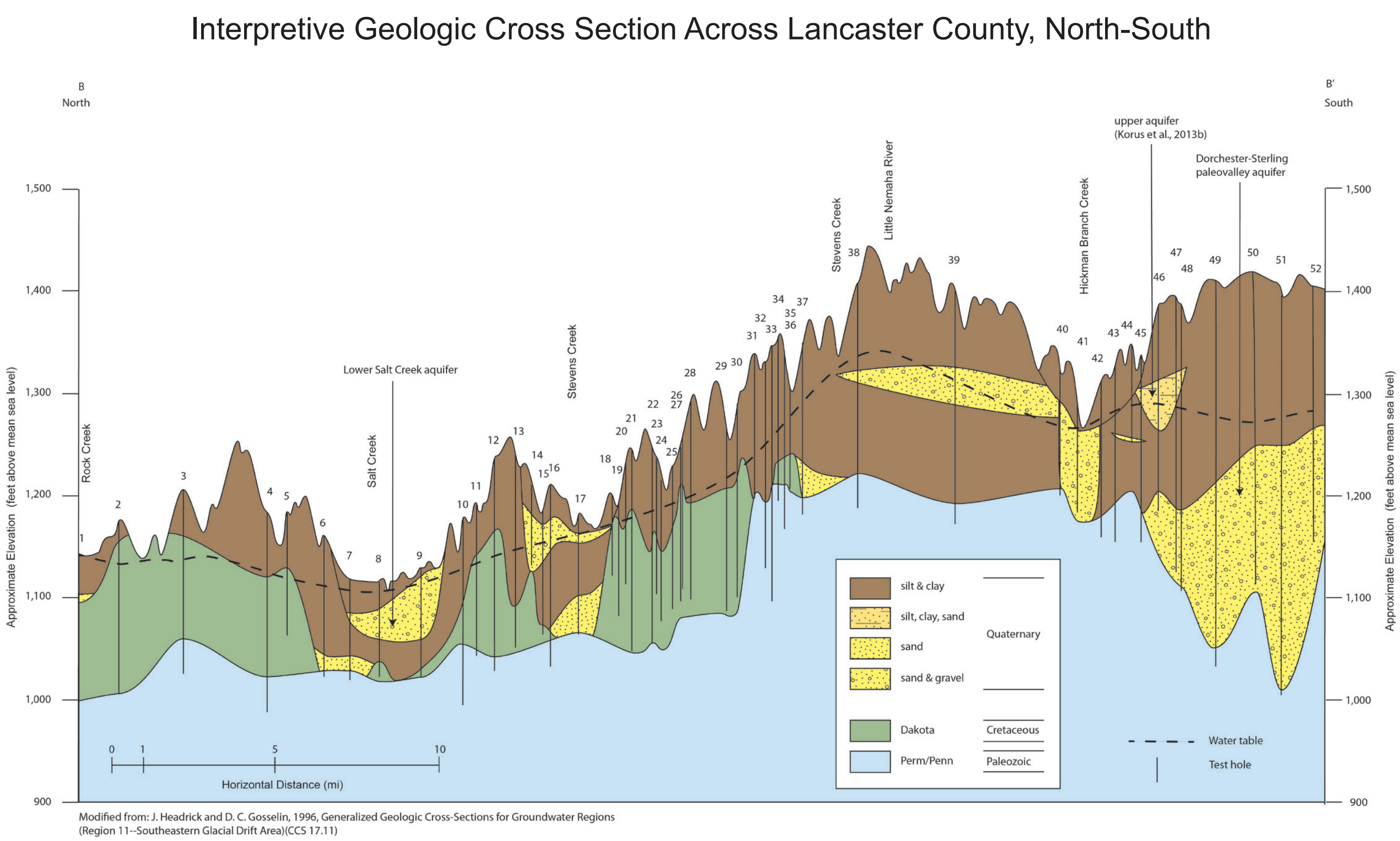


Figure 5. Interpretive Geologic Cross Section B-B', North-South. The location of this cross section is shown on figure 3. The dashed horizontal line is an estimated water level elevation and the solid vertical lines represent the locations (Appendix B) of bore holes or registered well logs. Loess, till, silt, and clay deposits are not subdivided.

Lincoln where the Dakota Group has been completely eroded in places and Quaternary deposits directly overlie Permian/Pennsylvanian bedrock. The south end of the section crosses into an area that was mapped in detail via an airborne electromagnetic survey (Korus et al., 2013b).

The position of the water level shown on both cross sections (Figs. 4 and 5) was extracted off the groundwater elevation in Quaternary aquifers map that will be discussed in the next section. The geologic units under the dashed lines are more likely to be saturated than the material above the line. Fine-grained Quaternary material is grouped together and labelled "silt & clay." Soil, loess, glacial till, silt, and clay are all included in this category and are not subdivided because their hydrogeologic properties are similar. Individual identification numbers for each well or bore hole used to construct the cross sections are available on the electronic version of the figure and in Appendix A.

Aquifers

The three main types of aquifers in Lancaster County are: 1) paleovalley aquifers; 2) localized sand and gravel deposits within glacial till; and 3) the Dakota aquifer. Previous statewide or nearly-statewide CSD publications focus on the hydrogeologic properties of the "principal aquifer" (e.g. Summerside et al., 2005). The concept of the principal aquifer is necessary for statewide maps because the geologic units that supply the majority of the water are not the same across the state. The downside of using the principal aquifer concept for a county map is that pertinent information about other aquifers is obscured. In Lancaster County the coarse-grained unconsolidated Quaternary deposits in paleovalleys and glacial till have been viewed as the principal aquifer. However, it is more accurate to think of the distinct sand and gravel units within the Quaternary as multiple, separate Quaternary aquifers.

Paleovalley aquifers are the primary sources of water to high-yield wells in the county. The two main paleovalleys in Lancaster County are the Dorchester-Sterling and Salt Creek paleovalleys. The Salt Creek paleovalley is filled with silt west of Lincoln, is not as deeply incised as the Dorchester-Sterling paleovalley, and is, therefore, not as significant an aquifer.

Quaternary material in the Dorchester-Sterling paleovalley aquifer in southern Lancaster County has been mapped in detail using Helicopter Electromagnetic (HEM) Surveys funded by Lower Platte South Natural Resources District, the Eastern Nebraska Water Resources Assessment, the Nebraska Department of Natural Resources, and the Nebraska Environmental Trust (Divine et al., 2009; Korus et al., 2013b; Divine and Korus, 2012). The surveys reveal two significant sand units above and within the paleovalley. The upper sand unit consists of stratified sands associated with glacial deposits. In the south-central part of Lancaster County this upper sand unit is a relatively narrow deposit, varying from 0.4 to 1.4 miles wide and 0 to approximately 185 feet thick (Korus et al., 2013b). In this part of the county, the bottom of the upper sand unit is higher than the incised paleovalley (Fig. 5). The lower sand unit consists of the sediments within the paleovalley called the Dorchester-Sterling paleovalley aquifer (Fig. 5). West of U.S. Highway 77 (Fig. 1) the upper sand unit becomes more laterally widespread and varies from 0 to approximately 220 feet thick. The deeper paleovalley fill appears to have been completely eroded in places by channelized deposits of the upper sand unit (Divine and Korus, 2012). In other places, the upper sand unit has only partially eroded the paleovalley fill, and the two sand units are in direct contact and constitute a single aquifer. In some locations, the two sand units are separated by a fine-grained deposit called an aquitard that can be as much as 185 feet thick, and the sand units are distinct aquifers (Divine and Korus, 2012). Where the geology becomes complex, both sand units are referred to collectively as the Dorchester-Sterling paleovalley aquifer.

The complex spatial relationship of Quaternary aquifers with each other and with fine-grained aquitards is important because it has a direct effect on the static and pumping water levels in wells. An unconfined aquifer is in direct connection with the atmosphere, which means it is typically shallow and has little or no fine-grained material deposited between it and the land surface. The elevation of water in an unconfined aquifer is colloquially called the water table (the technical definition of the water table is more complicated). The water table is at or below the top of the aquifer. When a well in an unconfined aquifer is pumped, the pore space between sand grains is drained and the elevation of the water table is lowered. A confined aquifer is not in direct contact with the atmosphere. The water in this type of aquifer is generally under pressure. When a well is installed in a confined aquifer, the pressure pushes the water up the well above the top of the aquifer. The elevation of water in a confined well is called the pressure head and the imaginary surface that would be created by connecting the pressure heads from multiple wells across an area is called the potentiometric surface. Simply put, the potentiometric surface is to confined aquifers what the water table is to unconfined aquifers. When wells in confined aquifers are pumped, the pressure head falls rapidly, but the pore spaces in the aquifer do not drain unless the aquifer is pumped extensively. Some aquifers are borderline between unconfined and confined types and are termed semi-confined. Additionally, some localized, shallow aquifers have a water level elevation that is significantly higher than the regional water table or potentiometric surface. These aquifers, called semi-perched aquifers, are not unusual in the upland areas of eastern Nebraska (Summerside et al., 2005).

The localized sand and gravel aquifers within glacial till were probably deposited by inter-glacial (between glacial advances) and sub-glacial (beneath ice sheets) melt waters. The locations and extents of these deposits are difficult to predict and map, and their yields are relatively small. These aquifers are best suited to supply domestic wells, although some may supply a few irrigation wells, particularly in the northwestern part of the county.

The Dakota aquifer is present in approximately three-fourths of Lancaster County; older Permian/Pennsylvanian rocks are the uppermost bedrock in the southeastern part of the county and in the northeast (Fig. 3). The Dakota aquifer is considered a secondary aquifer because the water can be high in salt and other dissolved minerals. However, the Dakota aquifer may supply relatively high-yield wells in many places where the Quaternary is thin or absent, if the water quality of the Dakota aquifer there is good. The Dakota aquifer was the primary source of water for the city of Lincoln until the early 1930s when a new well field was developed along the Platte River near Ashland, Nebraska. The new well field was necessary due to rising salinity in the Dakota aquifer wells and a growing population in Lincoln (Lincoln Water System, 2014).

Maps for the Quaternary and Dakota aquifers are presented separately in this atlas, but many wells draw water from both. Readers who are using this atlas to assess the amount of water present at a specific location should consider aspects of both the Quaternary and Dakota aquifers and be aware of the water quantity and quality in both aquifers at that location.

Well house of a former Lincoln Water System well screened in the Dakota aquifer.

HYDROGEOLOGIC MAPS

Groundwater Elevation in Quaternary Aquifers

Salt Creek is the primary drainage in Lancaster County. In the northern part of the county, groundwater consistently flows towards Salt Creek or its tributaries (Fig. 6). In the southern part of the county, there are several groundwater highs that produce variable groundwater flow directions. The Quaternary geology within the Dorchester-Sterling paleovalley in southern Lancaster County is also very heterogeneous (Korus et al., 2013b; Divine and Korus, 2012), which adds to the complexity of groundwater flow in the southern part of the county.

The groundwater elevation map (Fig. 6) was made using water level information collected between 1990 and 2013 from wells screened in Quaternary aquifers, and, therefore, the contours on this map should be interpreted as average conditions during that time. Any information collected in the June through September period was not used due to the possibility that it could reflect a non-static summertime water level. Most of the wells providing data used to make this map have only one water level available that was measured by the driller at the time the well was installed. However, some of the wells are monitoring wells in which the water level is repeatedly measured at intervals over a period of time. In these wells, the average water level between 1990 and 2013 (excluding summer months) was used in figure 6. In any given year the water levels in Lancaster County may fluctuate both up and down, but the groundwater level has not changed significantly due to irrigation development in Lancaster County overall (Young et al., 2013).

The groundwater elevation at streams was estimated by identifying where the topographic contours cross streams using U.S. Geological Survey 7.5-minute topographic maps. Topographic maps were mostly produced in the 1960s and photorevised in the 1970s or 1980s. Groundwater elevation points were only picked on stream reaches included in the National Hydrographic Dataset GIS layer (NDNR, 2012). Because the topographic maps are older than the measured groundwater level data, most of the groundwater levels estimated at streams are from a different time frame than the groundwater elevation data collected from wells.

Figure 7 shows hydrographs (water level changes over time) from three wells installed very close to one another, but screened in different sand units either above or within the Dorchester-Sterling paleovalley aquifer (site 09EN07 in Korus et al, 2013b). The water level in the uppermost sand unit is at a much higher elevation than the regional water level represented in the two deeper sand units. The gradual rises and falls of this hydrograph reflect natural seasonal variations in the water level, which is typical of an unconfined aquifer. This aquifer may also be classified as perched or semi-perched because it is a localized aquifer whose water level is significantly higher than the regional water level. Technically, a perched aquifer is separated from the regional aquifer by an unsaturated zone and a semi-perched aquifer is not. It is not known if an unsaturated zone exits under the shallow well of figure 7.

The hydrographs of wells installed in the deeper sand units shown on figure 7 share a similar static water elevation, but the pressure head in the deeper well (218 feet) declines more noticeably in the summer (possibly due to pumping of a nearby well) than that of the well installed at 135 feet. Both of these wells are in a confined part of the deep paleovalley fill (Korus et al., 2013b). As confined wells, the pressure heads are isolated from natural seasonal variations, but may change rapidly in response to local pumping.

The difference in water levels shown on figure 7 illustrates the difficulty in producing groundwater elevation maps and depth to water maps for the Quaternary aquifers in Lancaster County, and in eastern Nebraska in general. Multiple aquifers may be present at different depths at one location, and they may or may not have similar water levels. Additionally, a regional aquifer may spatially change between confined and unconfined. The water levels collected from wells in the aquifer would represent either an unconfined water table or a confined potentiometric surface. The Dorchester-Sterling paleovalley aquifer is both confined and unconfined depending on the location, and a combined water table/potentiometric surface map shows that the water levels are relatively continuous between the unconfined and confined areas (Korus et al., 2013b). Given these complexities and others (especially regarding well construction), it is not practical to separate water levels collected in unconfined and confined wells in order to make both water table and potentiometric surface maps. The reader should, however, be aware that this grouping has occurred in this atlas. The lithologic log and static and pumping water levels specific to an individual well may be available on-line at www.dnr.nebraska.gov or from the driller who installed the well, should a reader wish to investigate specific locations in more detail.

Depth to Water

The depth to water map (Fig. 8) was made by subtracting the groundwater elevation of the Quaternary aquifers (Fig. 6) from the digital elevation model of land surface resampled to 100 meter grid size. The depth to water map (Fig. 8) reflects surface topography nearly everywhere in the county, indicating that groundwater is shallow in stream valleys and deeper under hill tops. This pattern is generally expected. The only deviation from this pattern

A Helicopter Electromagnetic (HEM) survey was flown over the Dorchester-Sterling paleovalley aquifer near the Sheldon power plant north of Hallam, Nebraska in 2009.

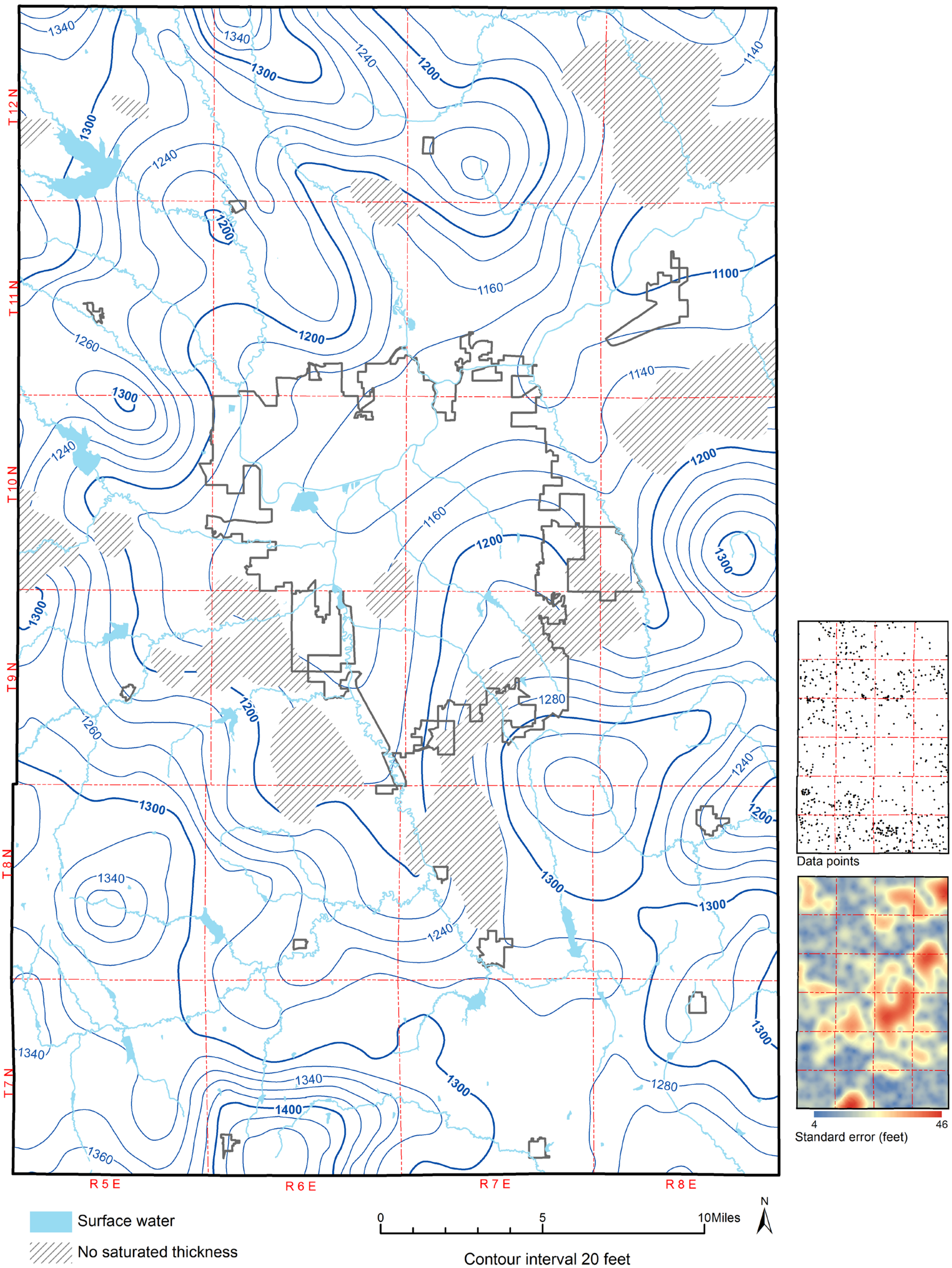


Figure 6. Groundwater Elevation in Quaternary Aquifers.

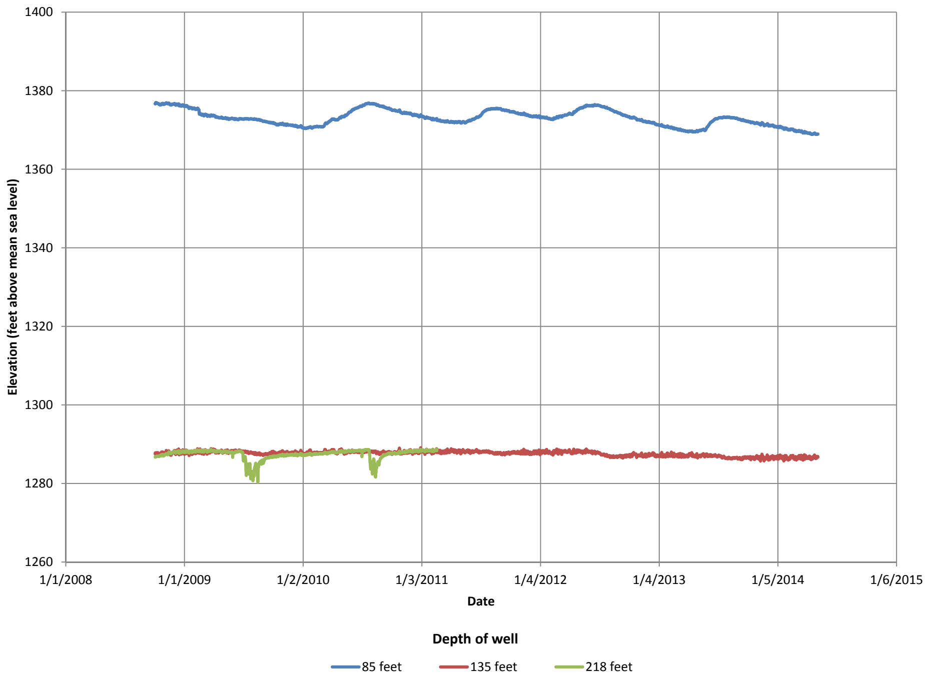


Figure 7. Well Hydrographs. Groundwater elevation changes over time for three monitoring wells screened at different depths.

Areas of greatest saturated thickness generally correspond to the paleovalleys that are depicted as bedrock lows on the elevation of bedrock map (Fig. 3). Both fine- and coarse-grained material is included in the calculation. The saturated thickness of the Quaternary is not the only indicator of the availability of groundwater because many Dakota aquifer wells are present in the areas shown with zero Quaternary saturated thickness. The error on this map is a combination of the errors and limitations associated with the groundwater elevation in the Quaternary aquifers and the elevation of bedrock maps.

Transmissivity of Quaternary Aquifers

Transmissivity is a measure of how much water an aquifer can transmit and is calculated by multiplying the hydraulic conductivity of the aquifer by saturated thickness. Wells installed in high transmissivity areas have higher potential yields than wells installed in lower transmissivity areas. For example, a transmissivity value of 50,000 gallons per day per foot (gpd/ft) could yield 500 gallons per minute (gpm) in a large diameter well, while a transmissivity of 3,000 gpd/ft could produce about 10 gpm in a domestic well (Holly, 1980). Most modern houses require a minimum of approximately 5 gpm.

Figure 10 shows the transmissivity of the Quaternary aquifers. The highest transmissivity in the Quaternary (greater than 50,000 gallons per day per foot) is in the Dorchester-Sterling paleovalley aquifer, primarily due to the thickness of the sediments. Transmissivity values greater than 20,000 gpd/ft occur in areas of the Salt Creek paleovalley. Areas estimated to have transmissivity values greater than 5,000 gpd/ft occur under parts of Lincoln and peripheral to the paleovalleys. Domestic wells exist in areas were the transmissivity is less than 5,000 gpd/ft, but their yields may not be ideal and the data become too uncertain to contour.

The transmissivity of Quaternary aquifers in Lancaster County was calculated using the same wells and test holes that were used to determine the elevation of the bedrock surface. There are numerous shallower bore holes in Lancaster County that were not used in the calculation because they do not fully penetrate the entire thickness of the Quaternary. The groundwater elevation in the Quaternary

occurs in the extreme southern part of the county where depth to water is shallower than topography would suggest. The Quaternary water level map (Fig. 6) indicates that a groundwater high exists in this location, which coincides with the headwaters of Spring Branch and the Middle Big Nemaha River.

Gray shaded areas on figure 8 indicate locations where the calculated water level is higher than ground surface. Shaded areas occur in many of the stream valleys. The water level is probably actually higher than the land surface where saline wetlands occur. Where saline wetlands do not exist, the water level might not actually be above ground surface. Much of the data in the stream valleys was inferred from topographic maps and it is possible that the elevated values in stream valleys represent measurement error. Additionally, if any parts of figure 6 represent pressure heads within confined aquifers, the depth to water on figure 8 could be misleading because a well would need to be drilled past the potentiometric surface into the confined aquifer.

Saturated Thickness of the Quaternary

The saturated thickness of the Quaternary map (Fig. 9) was made by subtracting the bedrock elevation (Fig. 3) from the groundwater elevation in Quaternary aquifers (Fig. 6). Places where Quaternary sediments are unsaturated generally correlate to locations of bedrock highs. These locations can be seen on the cross sections (Figs. 4 and 5) where the water level line intercepts the bedrock layers.

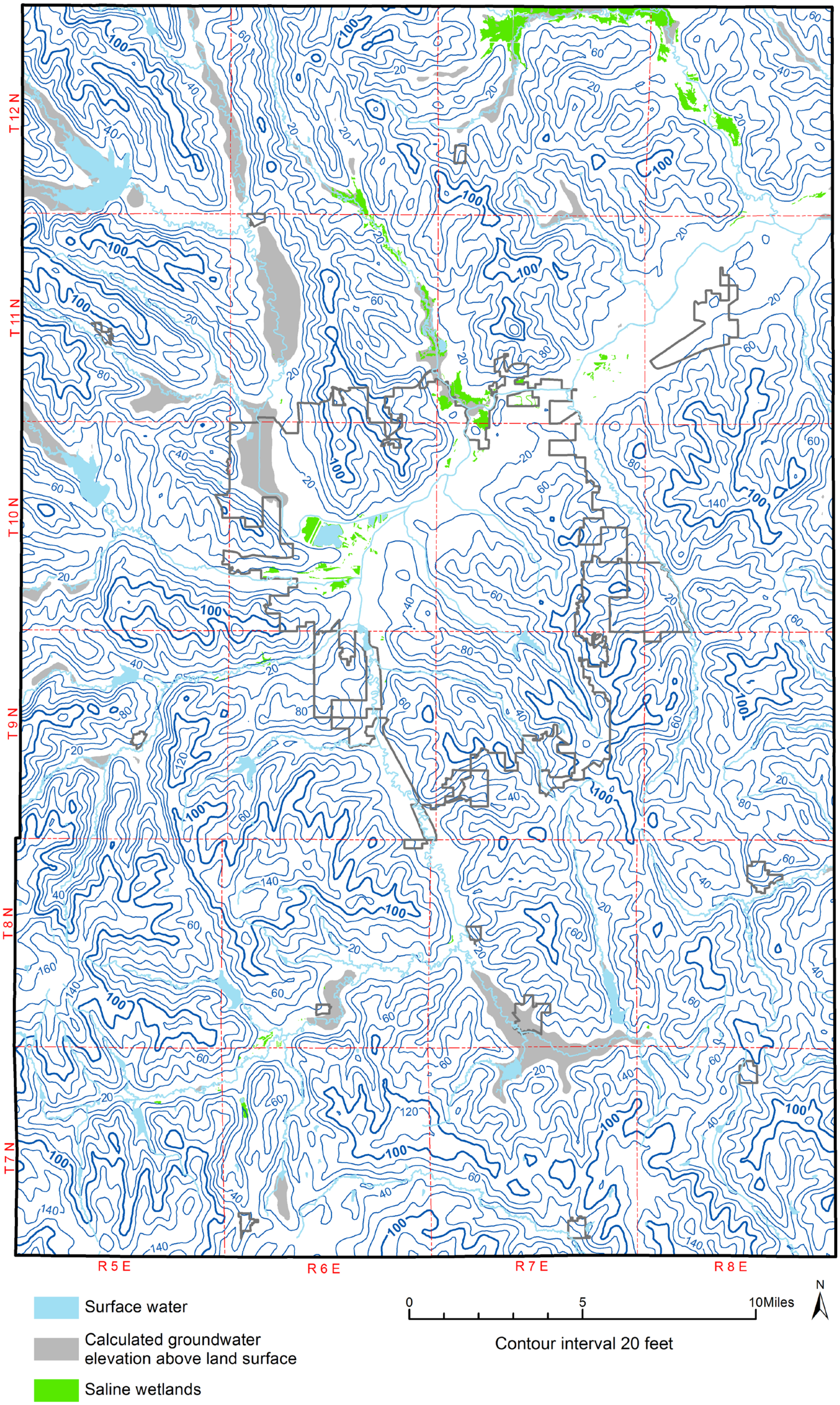


Figure 8. Depth to Water.

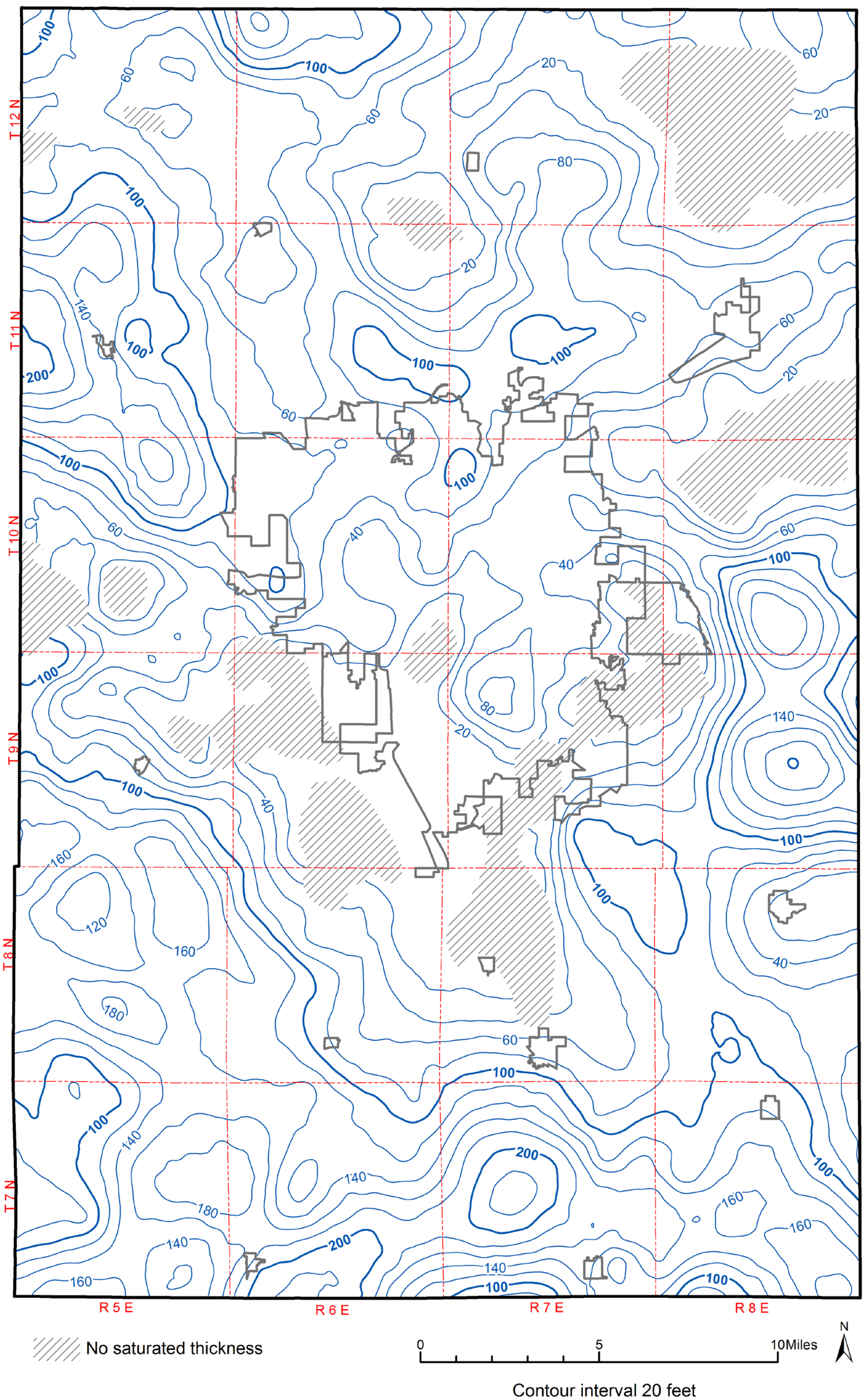


Figure 9. Saturated Thickness of the Quaternary. The greatest saturated thickness occurs in the Dorchester-Sterling paleovalley aquifer. Hachured areas have no calculated saturated thickness in the Quaternary.

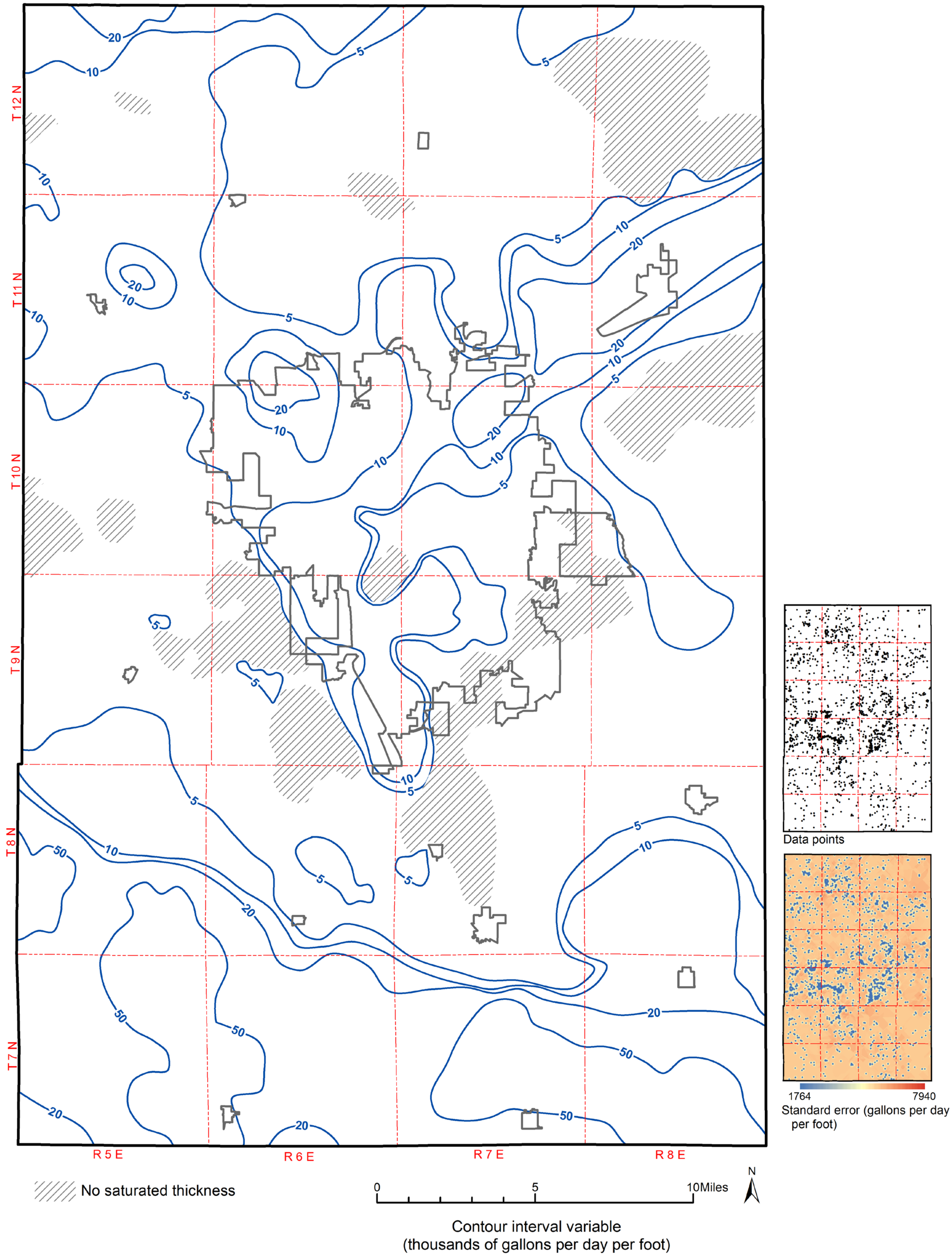


Figure 10. Transmissivity of Quaternary Aquifers.

aquifers map (Fig. 6) was used to identify unsaturated units, which were removed from the calculation because only saturated units contribute water to a well. A hydraulic conductivity value was assigned to each unit on a geologic log based on the geologic descriptions. The values assigned were very similar to the values CSD previously used to make 1:250,000 scale transmissivity maps. These hydraulic conductivity values were derived from an unpublished and undated report by E.C. Reed and R. Piskin, Conservation and Survey Division, University of Nebraska (Summerside et al., 2005).

The transmissivity lines calculated for this atlas correspond fairly well with the 1:250,000 scale map developed in 2005 and transmissivity calculations from aquifer tests (Holly, 1980; Korus, 2011; U.S. Geological Survey, 2009). Comparison of the transmissivity estimates based on lithology versus the aquifer tests suggest that transmissivity estimates based on lithology may be higher than those based on aquifer tests. Summerside et al (2005) noticed the same relationship, and suggested the higher estimates based on lithology are possibly due to the sampling techniques commonly used by drilling contractors. These techniques generally involve collecting cuttings with a shovel, which is not the most effective way of collecting silt and very fine sand, which tends to stay suspended in the drilling fluid. Missing fine-grained sediment will lead to an overestimation of hydraulic conductivity and transmissivity based on flawed estimates of grain-size. Additionally, the transmissivity in confined wells may be overestimated using the grain-size method because the pressure head could result in unsaturated units being included in the calculation.

The standard error associated with figure 10 is uniformly higher across the entire map area than the standard error associated with the other maps in this atlas. This distribution of error indicates that the standard deviation of transmissivity values is high. Highly variable transmissivity values in the Quaternary are not surprising, given that the Quaternary aquifers themselves are variable and the methods used to calculate transmissivity rely on the subjective description of sediments made by many different people. Given the elevated standard error, readers should be especially careful to use the Quaternary transmissivity values as generalized best estimates and not as definite values at the field scale.

Groundwater Elevation in Bedrock

The Dakota aquifer can be described as unconfined to semiconfined near Salt Creek northeast of Lincoln, where it is in hydraulic connection with overlying Quaternary aquifers (Druliner and Mason, 2001). Over the rest of the county, the Dakota aquifer may be either confined

Observation wells being monitored during an aquifer test in Burt County, Nebraska.

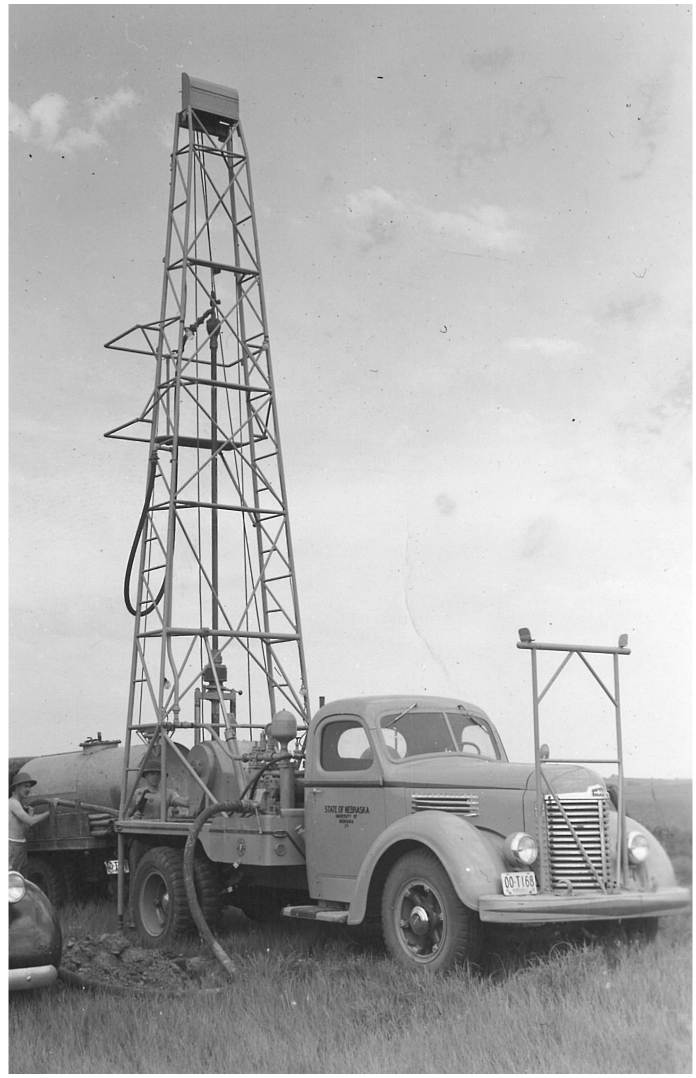
or unconfined (Anderson and Gosselin, 1999). Water levels collected from wells installed in the Permian/ Pennsylvanian bedrock may be either confined or unconfined depending on how deeply the well was drilled into the bedrock and the degree of weathering or fracturing of the limestone bedrock.

The greatest hydrologic heads in bedrock occur in the northwestern corner and in the southern parts of the county. Although few data points are present in these locations, a more regional water level map of the Dakota aquifer confirms a similar trend (Korus et al., 2013a). In the vicinity of Salt Creek northeast of Lincoln, the water levels in the Quaternary and Dakota aquifers are very similar, as expected given their hydrologic connection. Water level contours in the Dakota aquifer are more gradual than in the Quaternary because they are not affected by surface topography to the same extent, but some of the overall trends are similar, including highs in the northwestern corner of the county and in the extreme south. Water level contours in the limestone bedrock area in the southeastern corner of the county do not coincide with the Quaternary water level contours in that area.

Figure 11 was made using data from wells that are screened entirely in bedrock. The wells were selected in a two part process. First, lithologic logs were reviewed to identify wells that terminated in bedrock. The screen intervals for these wells were then downloaded from the Nebraska Department of Natural Resources registered well database and compared to the elevation of bedrock map (Fig. 3). Wells that were possibly screened across both Quaternary and Dakota aquifers were manually reviewed and omitted if appropriate. As on the Quaternary water level map, only water levels recorded between 1990 and 2013, excluding summer months, were used. The greatest density of bedrock wells is around the southern half of Lincoln where the acreage development is fairly dense and transmissivity of Quaternary aquifers is low.

Transmissivity of the Dakota Aquifer

Transmissivity is a hydrologic parameter that is a function of saturated thickness and the hydraulic conductivity of that saturated material. It is typically calculated using wells that fully penetrate an aquifer. Many of the wells in the Dakota aquifer in Lancaster County do not extend to the bottom of the aquifer, and no effort was made to determine which (if any) of the wells on figure 12 are fully penetrating. However, calculating the transmissivity of wells that at least partially penetrate the aquifer will indicate a minimum productivity of the aquifer. Figure 12 should be viewed as a minimum estimate.



Conservation and Survey Division, UNL

Geologists drilling a test hole northwest of Raymond, Nebraska, in 1948.

The highest transmissivity calculated in the Dakota aquifer (greater than 10,000 gpd/ft) is generally under and around Lincoln (Fig. 12). This productivity is well-documented because the aquifer served as the first municipal water supply for the city. Historic aquifer tests performed at wells near Antelope Creek were used to calculate transmissivity values that ranged from 56,000 gpd/ft to 72,000 gpd/ft. Discharge varied from 520 gpm to 1,090 gpm (Singleton, 1966). Isolated areas of calculated transmissivity greater than 10,000 gpd/ft occur locally in the county. Areas where the Dakota Group is present, but transmissivity is less than 5,000 gpd/ft, occur on the west side of the Dorchester-Sterling paleovalley aquifer and in a part of the northwestern part of the county. Under the Dorchester-Sterling paleovalley aquifer, the calculated transmissivity may appear low due to a lack of data and not reflect the actual transmissivity of bedrock. In the northwestern part of the county numerous domestic wells are present, even

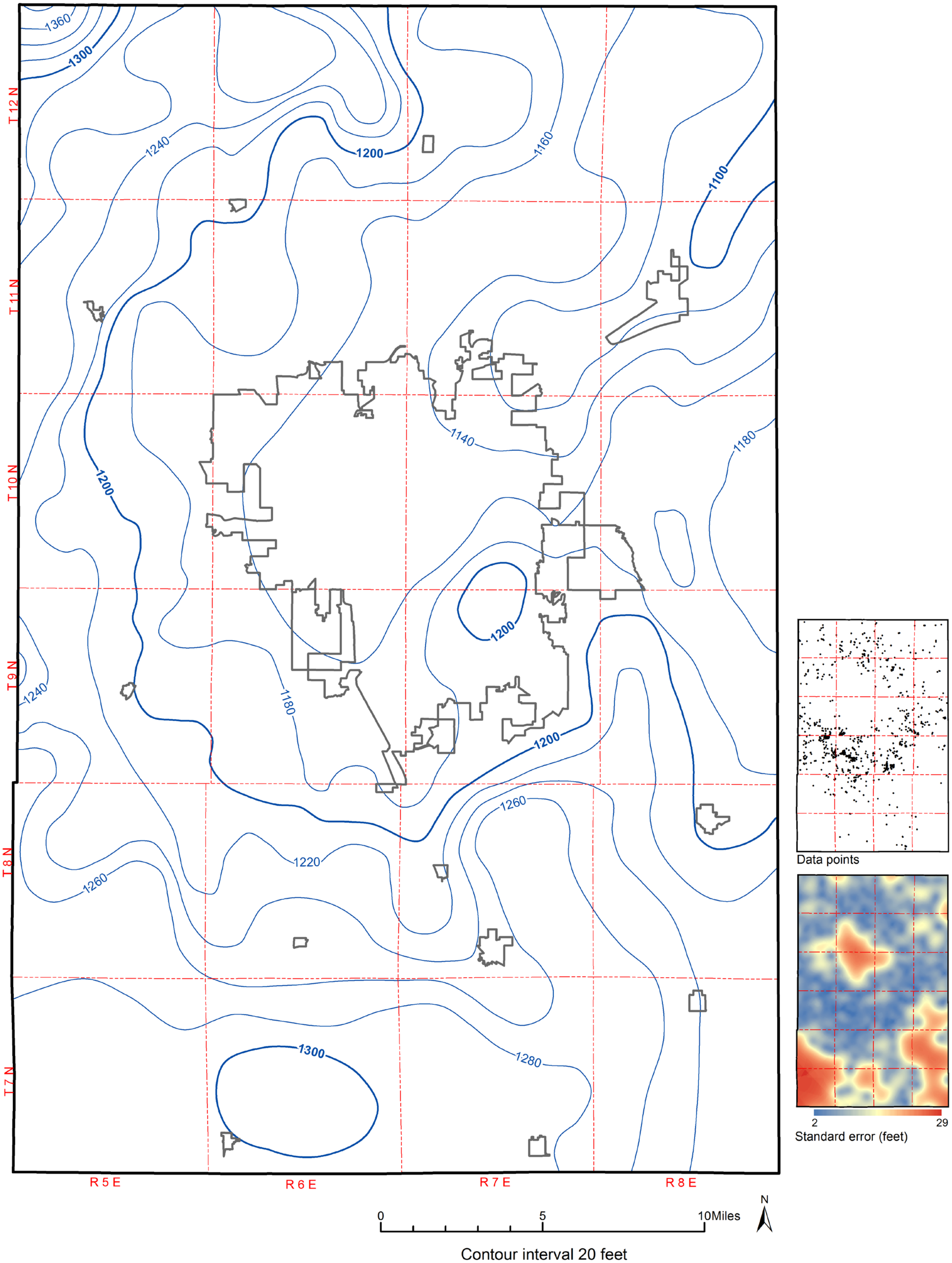


Figure 11. Groundwater Elevation in Bedrock.

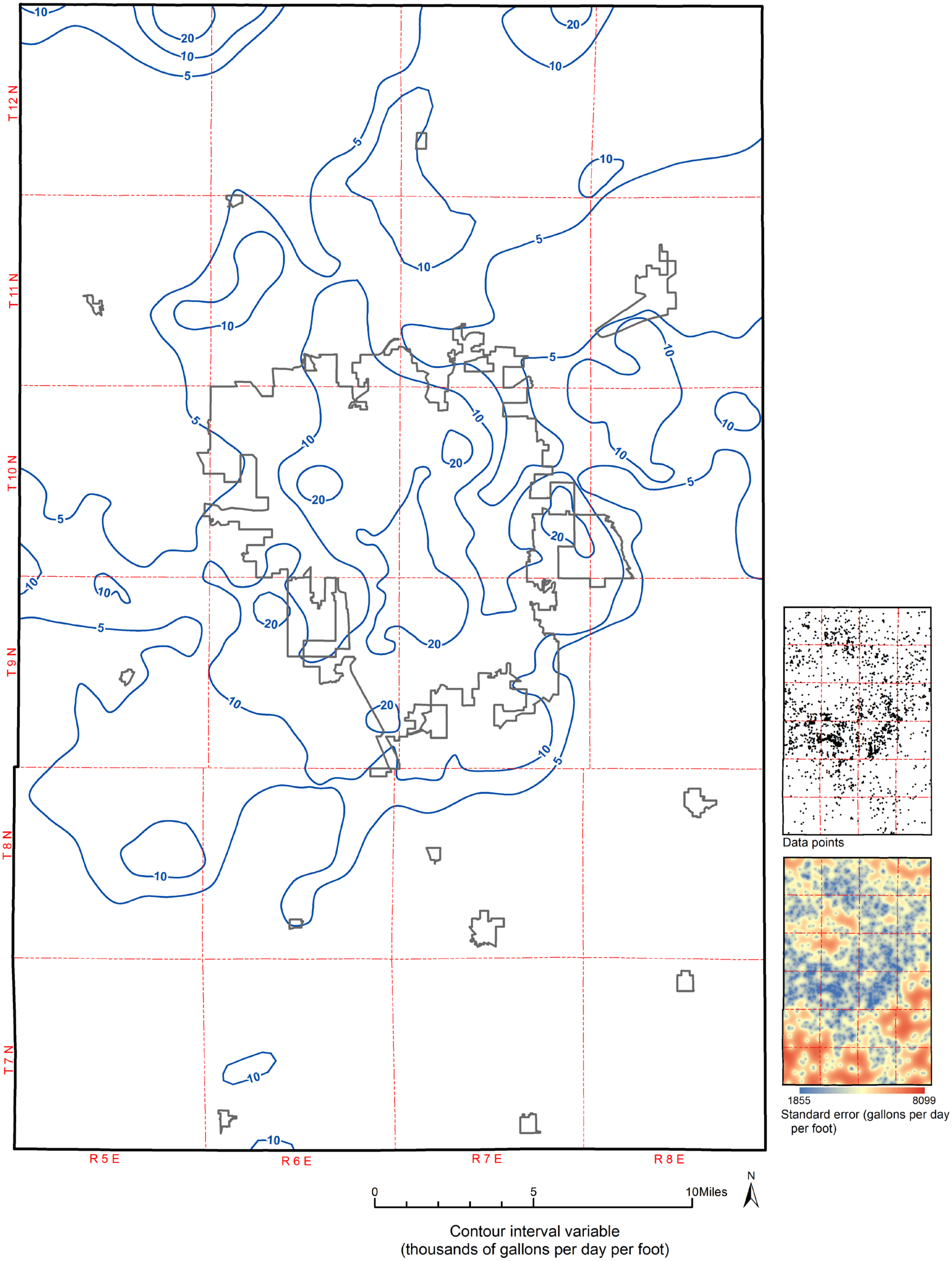


Figure 12. Transmissivity of the Dakota Aquifer.

though this area has low (<5,000 gpd/ft) transmissivity in both Quaternary and Dakota aquifers. The transmissivity values in this area are lower than in surrounding areas, but the Quaternary and Dakota aquifers do provide enough water for domestic wells, especially if a well is screened in both aquifers.

Areas where the Dakota aquifer is absent have virtually no bedrock transmissivity. Some wells do extract water from fractured limestone, but transmissivity values do not apply in fractured bedrock. A limited number of limestone wells have been developed in the vicinity of Bennet (Goodenkauf, 1978) and Hickman.

The transmissivity values depicted on figure 12 are based on hydraulic conductivity values estimated from lithologic descriptions, the same method used to make the transmissivity of the Quaternary map (Fig. 10). The Dakota Group is not completely saturated in Lancaster County (for example, see Fig. 4). Unsaturated bedrock units were identified using the groundwater elevation in the Quaternary aquifers map and removed from the calculation. The Quaternary water level elevation was used because water levels from confined wells may represent much of the data used to make the groundwater elevation in the Dakota aquifer map (Fig. 11), which would in all likelihood lead to an even greater overestimation of transmissivity than that caused by confined Quaternary wells in the calculation of Quaternary transmissivity. It is possible for the regional groundwater elevation of the Quaternary to intersect bedrock because of the large topographic relief on the Cretaceous-Quaternary contact.

Recharge

The focus of the preceding maps has been the accessibility of groundwater in aquifers for pumping. Fortunately, water also enters aquifers through a process called recharge. Directly measuring recharge is very difficult, so scientists have estimated recharge using different methods. A recent study conducted in eastern Nebraska estimated an average recharge rate of 2.3 inches (Gates et al., 2014) and a statewide map (Szilagyi and Jozsa, 2012) indicates that the net recharge ranges from 8 inches to -8 inches in Lancaster County, where negative values indicate that more water evapotranspires than recharges. In Lancaster County these negative values are associated with evaporation from lakes, especially Branched Oak and Pawnee lakes.

The methods by which water enters aquifers and the locations where recharge occurs are not well understood. A recent study in eastern Nebraska found that the amount of silt and clay in the glacial till greatly affects recharge. Approximately 40% to 80% of recharge occurs in lowlands and incised stream valleys where glacial till is absent (Gates et al., 2014).

Instrumentation installed in Burt County, Nebraska (left), and north of Firth, Nebraska (right), used to estimate recharge.

WATER QUALITY

Salinity and Mineralization

Water chemistry types are assigned based on the relative amounts of ions dissolved in the water (Black, 1966). Water collected in the Salt Creek and the Dorchester-Sterling paleovalley aquifers are mostly calcium carbonate to calcium-magnesium-sodium carbonate water types (Druliner and Mason, 2001; Korus et al., 2013b). However, the water in wells installed toward the bottom of the Dorchester-Sterling paleovalley has increasing sodium chloride, sulfate, and total dissolved solid concentrations with depth (Druliner and Mason, 2001). This highly mineralized and/or salty water might occur for two reasons: 1) either deep groundwater has had extended exposure to minerals in the aquifer and some of those minerals dissolved into the groundwater (Druliner and Mason, 2001); or 2) saline water originating in the Permian/ Pennsylvanian rocks has migrated upward through the Dakota Group into the Quaternary aquifers either due to a natural upward gradient (Sorenson, 2005; Harvey et al., 2007) or to an induced upward gradient produced by pumping (Gosselin et al., 2001).

A compilation of 241 water samples collected in Lancaster County for chloride analysis (mostly between 1993 and 2013) is shown in figure 13. The well use types include commercial, domestic, irrigation, municipal, and monitoring. Analysis of the data indicate a statistically significant positive correlation between well depth and chloride concentration (Spearman's Rank Correlation, n=241, p=0.0073, correlation coefficient=0.173). This correlation is consistent with the results of previous studies (e.g. Druliner and Mason, 2001; Gosselin et al., 2001; Harvey et al., 2007) showing that chloride concentrations tend to increase with depth.

Vertical chemistry profiles in wells can be complex and difficult to predict, possibly because they are affected by both the recharge and pumping history of the well (Gosselin et al., 2001; Dreeszen, 1997). When the data presented in figure 13 are separated by well use, only monitoring wells show a statistically significant correlation between well depth and chloride concentration (Spearman's Rank Correlation, n=34, p=0.00365, correlation coefficient=0.487). This correlation is stronger than that observed in the data set as a whole, potentially because monitoring wells are pumped only for sampling purposes and the vertical chemistry profile has not been mixed to the same extent as wells of other use types. Figure 14 shows chloride data graphed with depth.

In-depth chemical analysis of saline water in Lancaster County suggests that the salinity was derived from halite. Halite is crystalline sodium chloride formed during the evaporation of water containing dissolved sodium chloride (Gosselin et al., 2001). Evaporite deposits have been documented in the Pennsylvanian rocks underlying the Dakota Group in Nebraska (Carlson, 1993; Korus and Joeckel, 2011) and the chemistry of sodium-chloride water in the Dakota aquifer is similar to the saline water collected from Pennsylvanian rocks. Additionally, upward gradients have been observed between Pennsylvanian rocks and the Dakota aquifer (Gosselin et al., 2001), indicating that the underlying Pennsylvanian rocks are probably the source of salinity to the Dakota aquifer water.

The presence of sodium chloride in groundwater is responsible for the occurrence of saline wetlands in Lancaster County. Saline wetlands most commonly occur in coastal areas, but in the case of Lancaster County, saline groundwater has migrated along flow paths from either cooler climate or higher altitude recharge areas to discharge zones in the flood plains of the Salt, Little Salt, and Rock Creeks (Harvey et al., 2007). Each of the three major saline wetlands in Lancaster County has distinct hydrologic systems that depend on the relationships between subsurface geology, geomorphic features of streams, and topography (Kelly, 2011).

Lincoln Saline Wetlands Nature Center in west Lincoln.

A drilling crew installs monitoring wells in the Dorchester-Sterling paleovalley aquifer north of Firth, Nebraska.

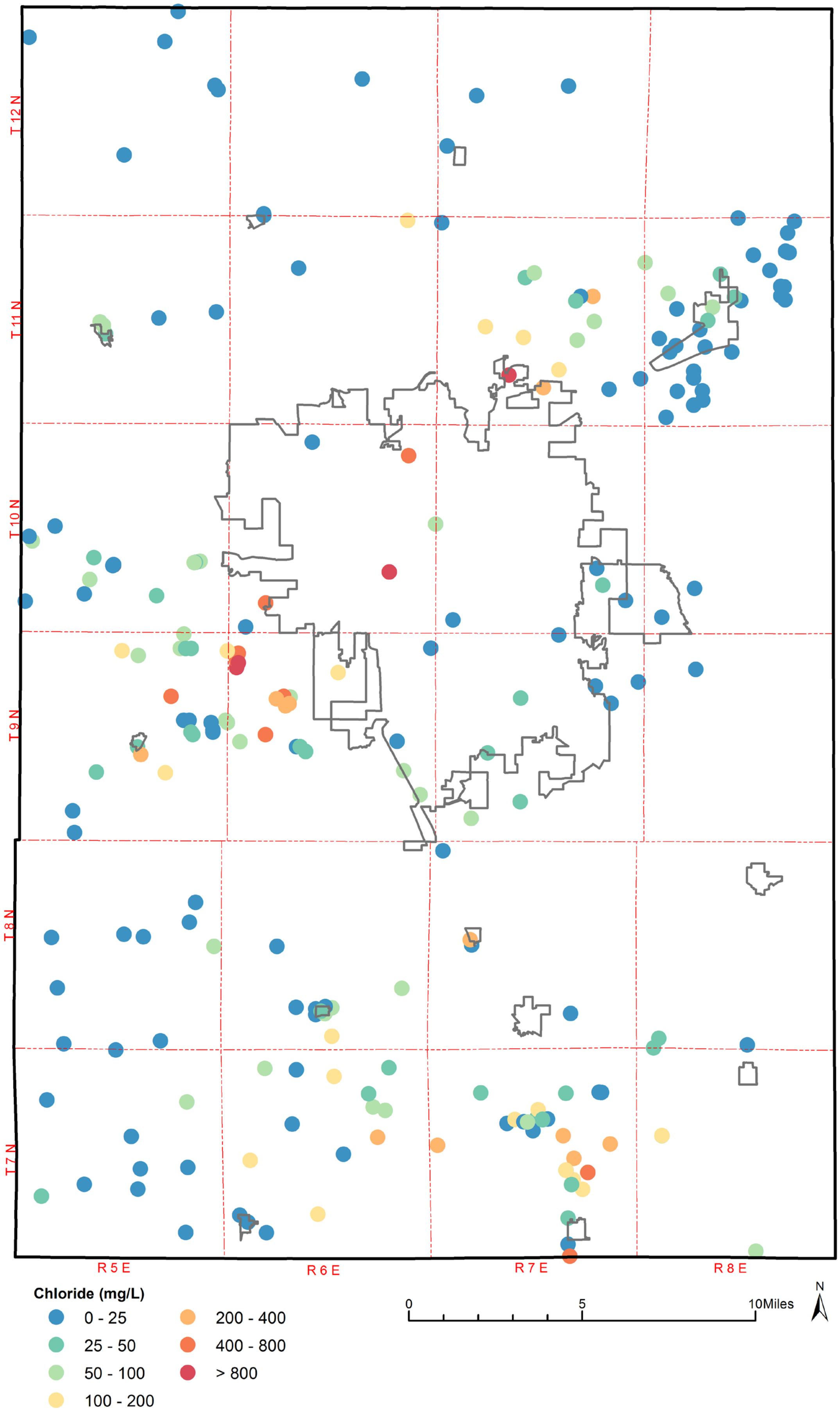


Figure 13. Chloride Concentration in Wells.

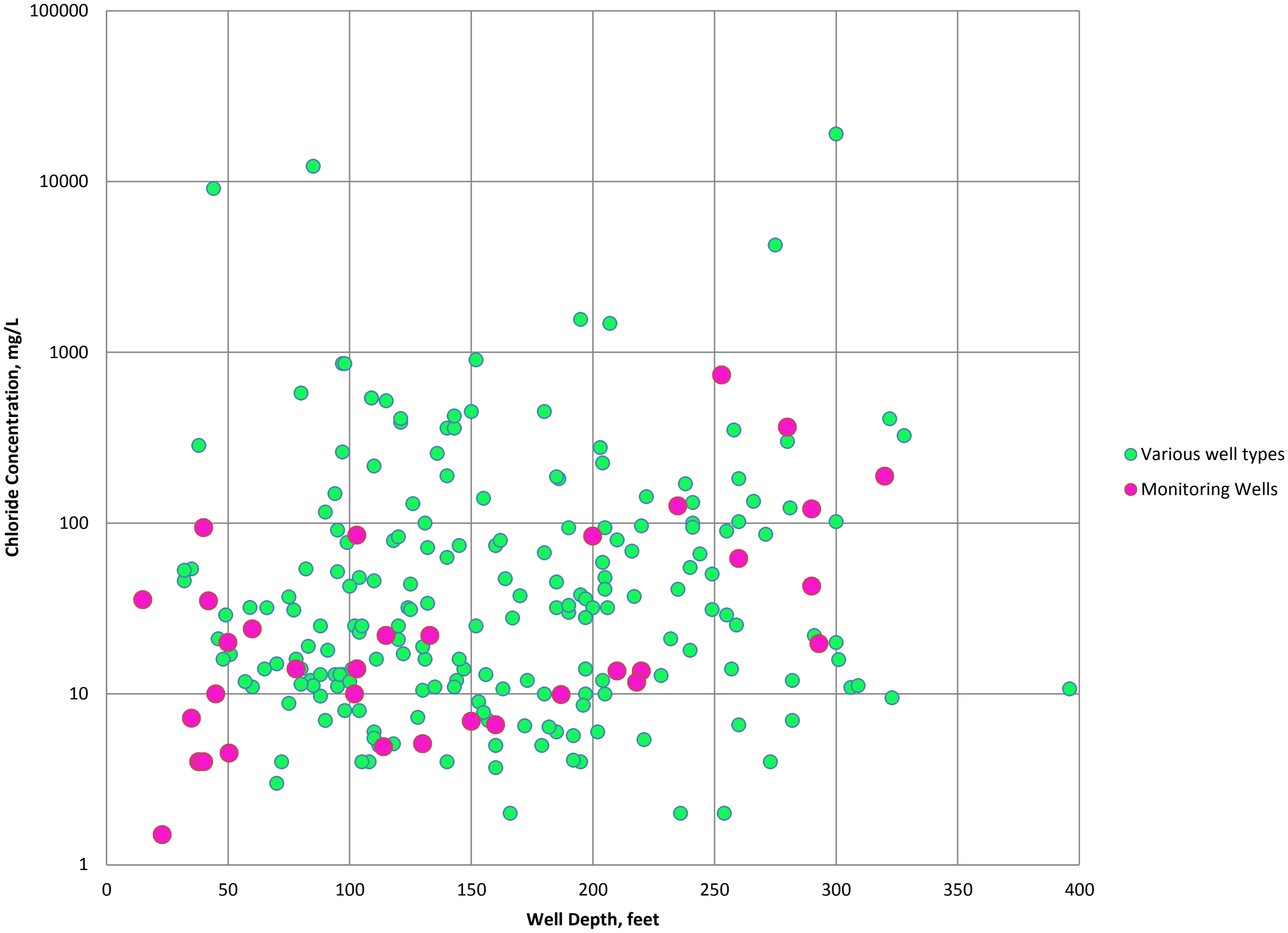


Figure 14. Chloride Concentration with Depth. Well types grouped in the "various" category include commercial, domestic, irrigation, and municipal.

A completed set of nested monitoring wells located north of Firth, Nebraska.

The potential salinity or mineralization of water in the Dakota aquifer has received a fair amount of attention because the Dakota is an important secondary aquifer and because progress in understanding the source of the salinity has only occurred relatively recently (e.g. Gosselin et al., 2001, Harvey et al., 2007, Kelly, 2011). The Dakota aquifer in Lancaster County also produces relatively fresh calcium-sodium-carbonate and calcium carbonate water in places where precipitation has recharged the aquifer (Anderson and Gosselin, 1999; Gosselin et al., 2001).

Nitrate

Shallow aquifers in Lancaster County generally receive sufficient recharge from precipitation so that elevated salinity or mineralization is not an issue. However, unconfined aquifers are vulnerable to nitrate contamination. The two main sources of nitrate are from agricultural application of fertilizer and from animal waste (generated in confined animal feeding operations).

The most recent nitrate concentrations in wells sampled between January 2004 and December 2013 are shown in figure 15. The data depicted on this map indicate that nitrate is below the maximum contaminant level (MCL) of 10 mg/L in 143 of 162 samples. In areas where nitrate concentrations are elevated, the Lower Platte South Natural Resources District has established Phase II groundwater management areas to reduce the amount of nitrate entering the aquifer. Phase II groundwater management is triggered in an area when 50% of the wells in the Natural Resources District monitoring network have concentrations at or above 5 mg/L and the nitrate concentrations are confirmed by a two-year verification study. Educational certification for nitrate applicators and increased cost-share for best management practices are initiated as ways to reduce the amount of nitrate entering groundwater. The Phase II areas in Lancaster County are in the Lower Salt Creek aquifer, the shallow Quaternary aquifer south of Hickman, and the Quaternary and Dakota aquifers around the community of Davey (LPSNRD, 2014b).

Wellhead protection area sign for Hickman, Nebraska.

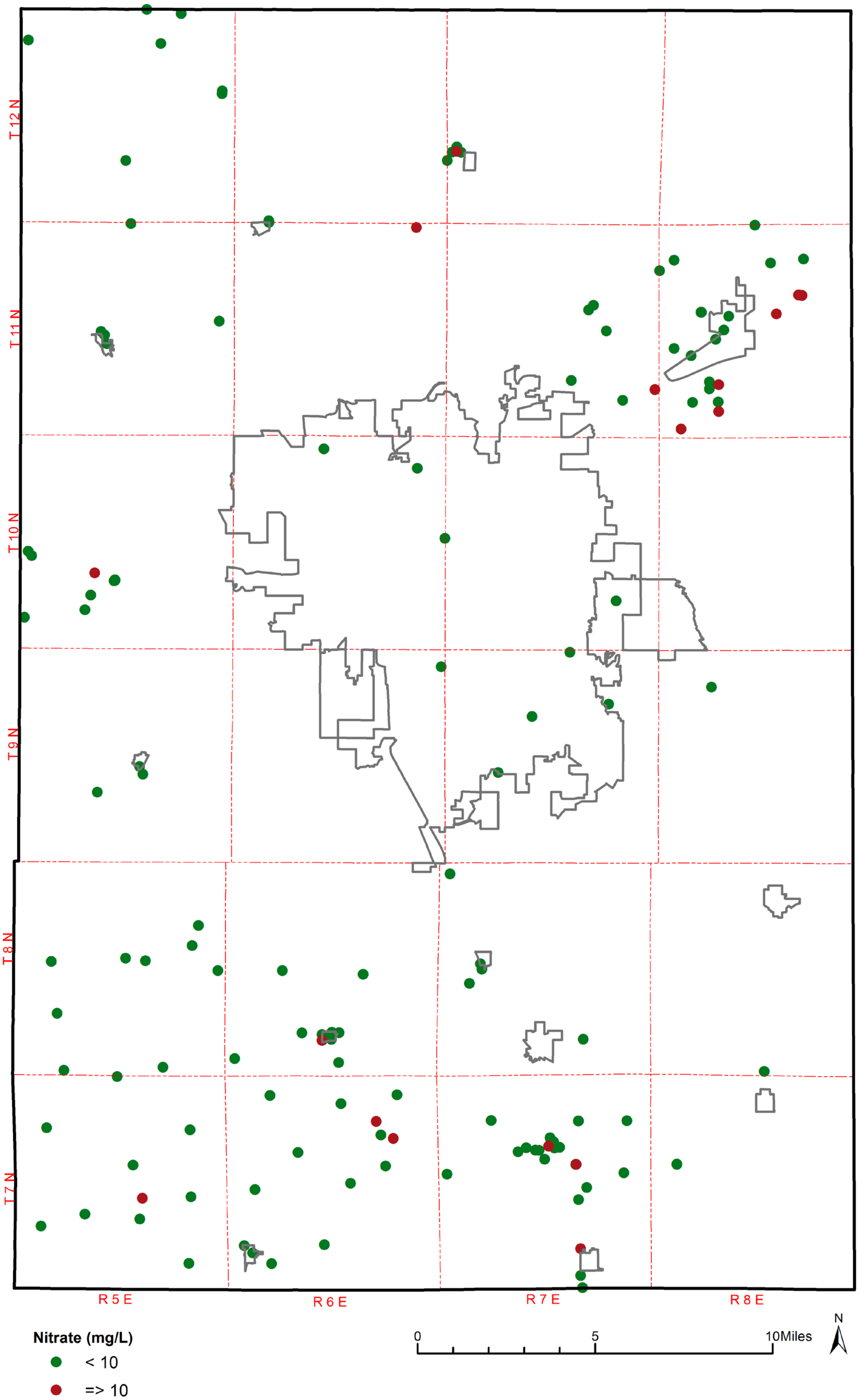


Figure 15. Nitrate Concentration in Wells.

SUMMARY

Three main types of aquifers exist in Lancaster County: 1) paleovalley aquifers, 2) localized deposits of sand within glacial till, and 3) the Dakota aquifer. The paleovalley aquifers and the localized sand units within the glacial till were deposited during the Quaternary Period which started 2.58 million years ago. The localized sand units within the glacial till are limited in extent, usually produce relatively low-yield wells better suited to domestic use than irrigation use, and generally do not have extensive hydrologic connection with other aquifers. The paleovalley aquifers are much larger, more continuous aquifers that produce higher well yields and support a wide variety of uses. The largest paleovalley aquifer in Lancaster County is the Dorchester-Sterling paleovalley which crosses the north part of Saline County, the southern part of Lancaster County, and ends in northwestern Johnson County. The second paleovalley also extends beneath several counties and crosses Lancaster County on the north side of Lincoln. It is shallower than the Dorchester-Sterling paleovalley. Parts of this paleovalley are filled with silt and clay which do not support high-yield wells. The saturated sand and gravel units of the Quaternary are considered the primary aquifers in Lancaster County.

The Dakota aquifer (formally the Maha aquifer) is an important secondary aquifer in Lancaster County and consists primarily of sandstone, with lesser amounts of sand and gravel. The Dakota aquifer is part of the Dakota Group, which includes thick sequences of mudstone, siltstone, and shale along with the sandstone, sand, and gravel. The lithologic variation within the Dakota is large both laterally and vertically, and difficult to predict. Some locations contain thick units of sandstone, while other locations will consist entirely of mudstone or shale. The Dakota Group is present in three-fourths of the county, but is absent in the southeastern part and in the northeast, where the first bedrock unit encountered is Permian/Pennsylvanian limestone and shale that was deposited approximately 252-323 million years ago. These rocks underlie the Dakota throughout the entire county and do not yield appreciable amounts of water.

In the northern part of Lancaster County, groundwater flow directions in both the Quaternary and Dakota aquifers are generally toward Salt Creek or its tributaries. The groundwater flow direction in the southern part of the county is variable due to local groundwater highs and the complex hydrogeologic framework of the Dorchester-Sterling paleovalley aquifer.

Transmissivity is the measure of how much water can be transmitted by an aquifer and is a function of the hydraulic conductivity of the aquifer and aquifer thickness. Higher transmissivity values indicate higher potential well yields. In Lancaster County higher transmissivity generally corresponds to the locations of the paleovalleys shown on the elevation of bedrock map, especially where the paleovalleys are filled with sand and gravel. However, transmissivity lines do not always correlate to the bedrock surface because lithology (and hydraulic conductivity) is variable and the sand units that occur within the glacial till are not related to the elevation of bedrock. The transmissivity contours reflect the characteristics of both the paleovalley aquifers and aquifers within the glacial till, and therefore the contours do not always correlate to bedrock lows and to the locations of paleovalleys.

Roca, Nebraska, water tower.

The water quality in Lancaster County is generally good. Nitrate concentrations in the Quaternary are elevated in the Lower Salt Creek aquifer northeast of Lincoln, in the vicinity of Davey, and south of Hickman. The Lower Platte South Natural Resources District has defined these locations as Phase II management areas in an effort to reduce nitrate concentrations. The natural water quality in the Dakota aquifer is sometimes salty or highly mineralized. Chloride concentrations are generally highest in Lincoln and around its north and west margins and generally increase with depth.

Yankee Hill, Nebraska, water tower.

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APPENDIX A

APPENDIX A. Bore hole locations for west-east cross section

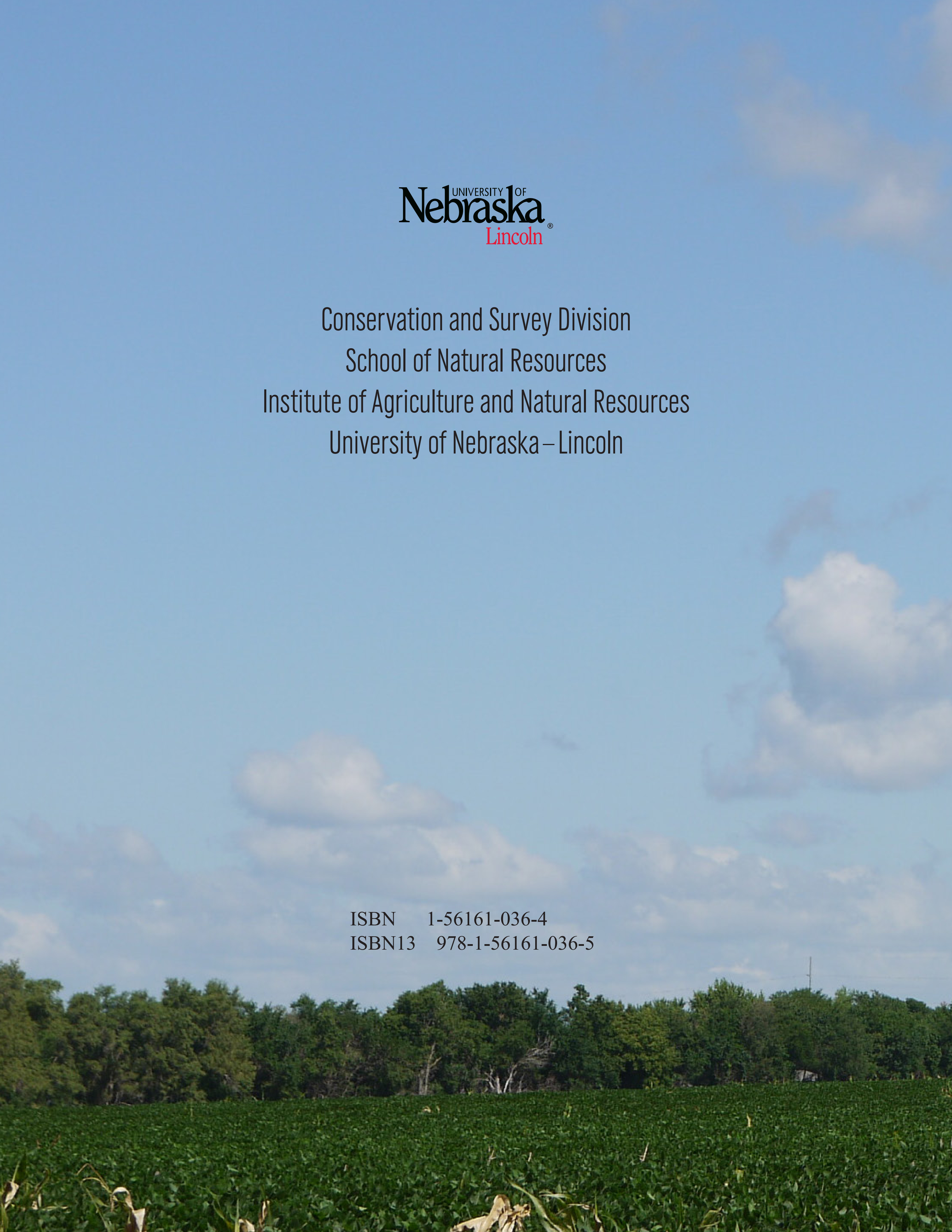
Number	Well ID	Township (North)	Range (East)	Section	Longitude	Latitude
1	3-B-44	11	4	36	-96.9111	40.8861
2	1-B-45	11	5	26	-96.8331	40.8866
3	175713	11	5	26	-96.8194	40.8878
4	1-B-42	11	5	25	-96.7957	40.8875
5	50957	11	6	33	-96.7560	40.8785
6	217733	11	6	33	-96.7408	40.8791
7	34-B-46	11	6	35	-96.7170	40.8753
8	145035	10	7	6	-96.6794	40.8690
9	8-A-73	10	7	6	-96.6629	40.8704
10	3-A-73	11	7	32	-96.6437	40.8717
11	23-B-46	11	7	33	-96.6301	40.8716
12	110936	11	7	34	-96.6111	40.8722
13	LAN-700	11	7	35	-96.5870	40.8710
14	143407	11	7	36	-96.5844	40.8717
15	70739	11	7	36	-96.5694	40.8727
16	107760	11	8	31	-96.5665	40.8745
17	70741	11	8	32	-96.5555	40.8746
18	175595	11	8	33	-96.5337	40.8721
19	138155	11	8	33	-96.5215	40.8710
20	1-A-68	11	8	35	-96.5012	40.8746
21	104944	10	8	2	-96.4851	40.8702

APPENDIX B

APPENDIX B. Bore hole locations for north-south cross section

Number	Well ID	Township (North)	Range (East)	Section	Longitude	Latitude
1	72-A-49	12	8	6	-96.5627	41.0449
2	118568	12	7	1	-96.5639	41.0306
3	71-A-49	12	8	18	-96.5645	41.0015
4	33-B-46	12	7	36	-96.5672	40.9653
5	153366	11	8	6	-96.5664	40.9567
6	104539	11	7	12	-96.5677	40.9400
7	9-B-49	11	8	18	-96.5667	40.9286
8	56526	11	8	18	-96.5660	40.9162
9	140162	11	8	30	-96.5642	40.8976
10	7-B-49	11	8	31	-96.5667	40.8804
11	107760	11	8	31	-96.5665	40.8745
12	8-B-49	10	7	1	-96.5673	40.8660
13	LAN 444-63-6	10	7	1	-96.5680	40.8570
14	110149	10	8	7	-96.5661	40.8507
15	217498	10	8	7	-96.5665	40.8452
16	6-B-49	10	7	12	-96.5675	40.8424
17	195405	10	8	18	-96.5672	40.8296
18	126740	10	7	24	-96.5680	40.8148
19	188410	10	8	30	-96.5669	40.8119
20	172912	10	8	30	-96.5667	40.8098
21	90794	10	7	25	-96.5698	40.8072
22	5-B-49	10	7	25	-96.5679	40.7988
23	123323	10	8	31	-96.5670	40.7970
24	157809	10	8	31	-96.5664	40.7947
25	93054	10	8	31	-96.5669	40.7896
26	90357	10	8	31	-96.5664	40.7860

Number	Well ID	Township (North)	Range (East)	Section	Longitude	Latitude
27	92236	10	8	31	-96.5673	40.7854
28	178408	9	8	6	-96.5655	40.7823
29	115448	9	8	7	-96.5662	40.7673
30	157571	9	8	7	-96.5650	40.7626
31	1-B-49	9	7	12	-96.5680	40.7554
32	180824	9	8	18	-96.5642	40.7514
33	218526	9	8	18	-96.5659	40.7490
34	188994	9	8	18	-96.5661	40.7461
35	136248	9	8	18	-96.5661	40.7437
36	98882	9	8	18	-96.5674	40.7414
37	178126	9	8	19	-96.5681	40.7356
38	13-B-49	9	8	30	-96.5655	40.7121
39	2-B-49	8	8	7	-96.5712	40.6691
40	11-B-49	8	8	31	-96.5718	40.6229
41	87139	8	7	36	-96.5753	40.6159
42	175650	7	7	1	-96.5732	40.6053
43	101476	7	8	6	-96.5686	40.6004
44	172073	7	7	1	-96.5767	40.5967
45	LAN-052	7	7	12	-96.5810	40.5940
46	92650	7	7	12	-96.5735	40.5885
47	101555	7	7	13	-96.5769	40.5812
48	185392	7	7	13	-96.5794	40.5799
49	16-EN-07	7	8	19	-96.5710	40.5660
50	219869	7	8	30	-96.5676	40.5491
51	70-A-49	7	8	31	-96.5715	40.5377
52	15-EN-07	7	7	36	-96.5730	40.5240



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Conservation and Survey Division
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